

A photograph of the IceCube detector building in Antarctica. The building is a large, blue, rectangular structure with several windows and doors. It is surrounded by a vast, flat, white expanse of snow and ice. In the background, there are two tall, white, cylindrical structures and a small wind turbine. The sky is a clear, bright blue.

Latest results from IceCube on high energy neutrino astrophysics

3rd - 5th November

Brookhaven Forum 2021

Opening New Windows to the Universe (BF2021)

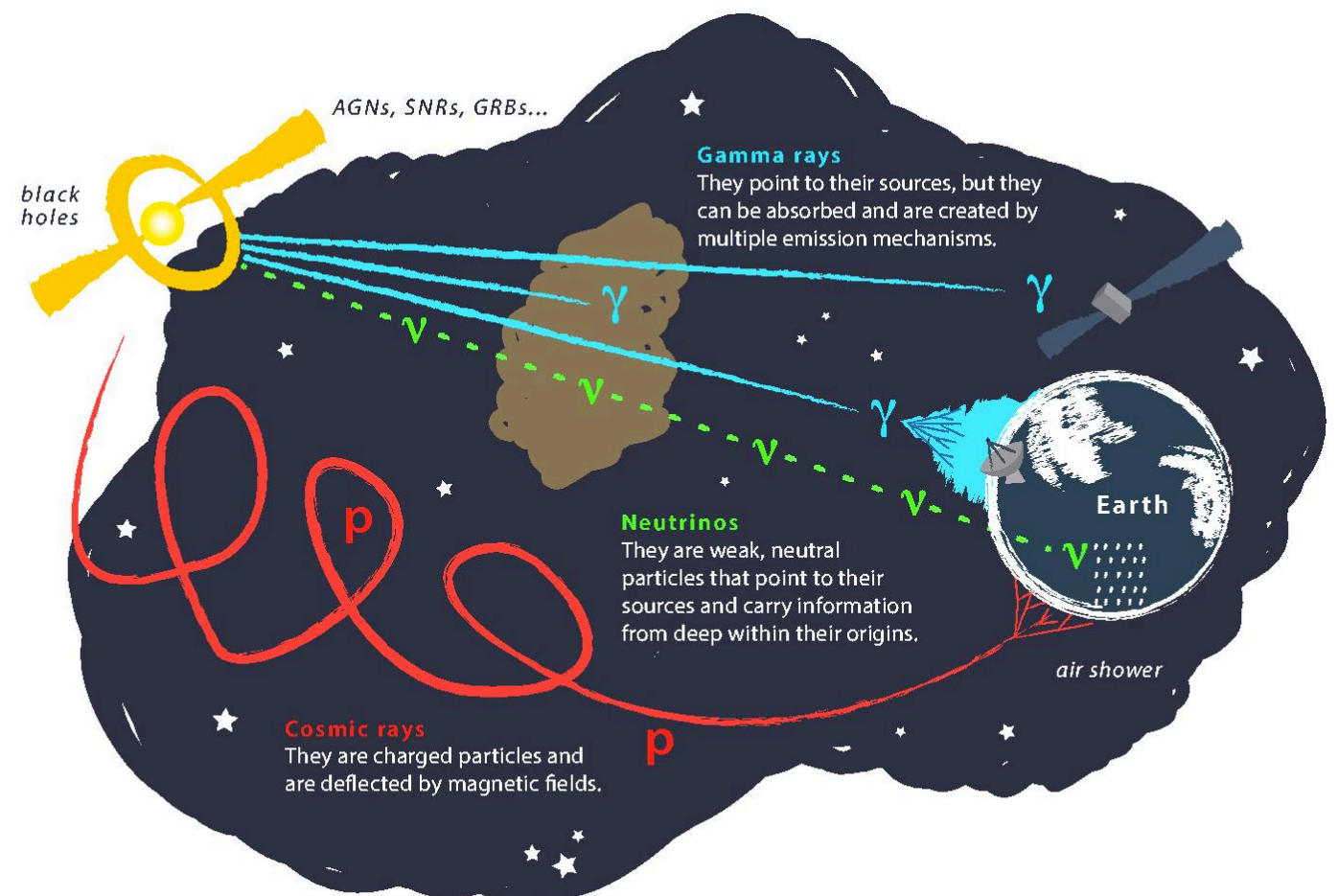
Ankur Sharma

for the IceCube Collaboration

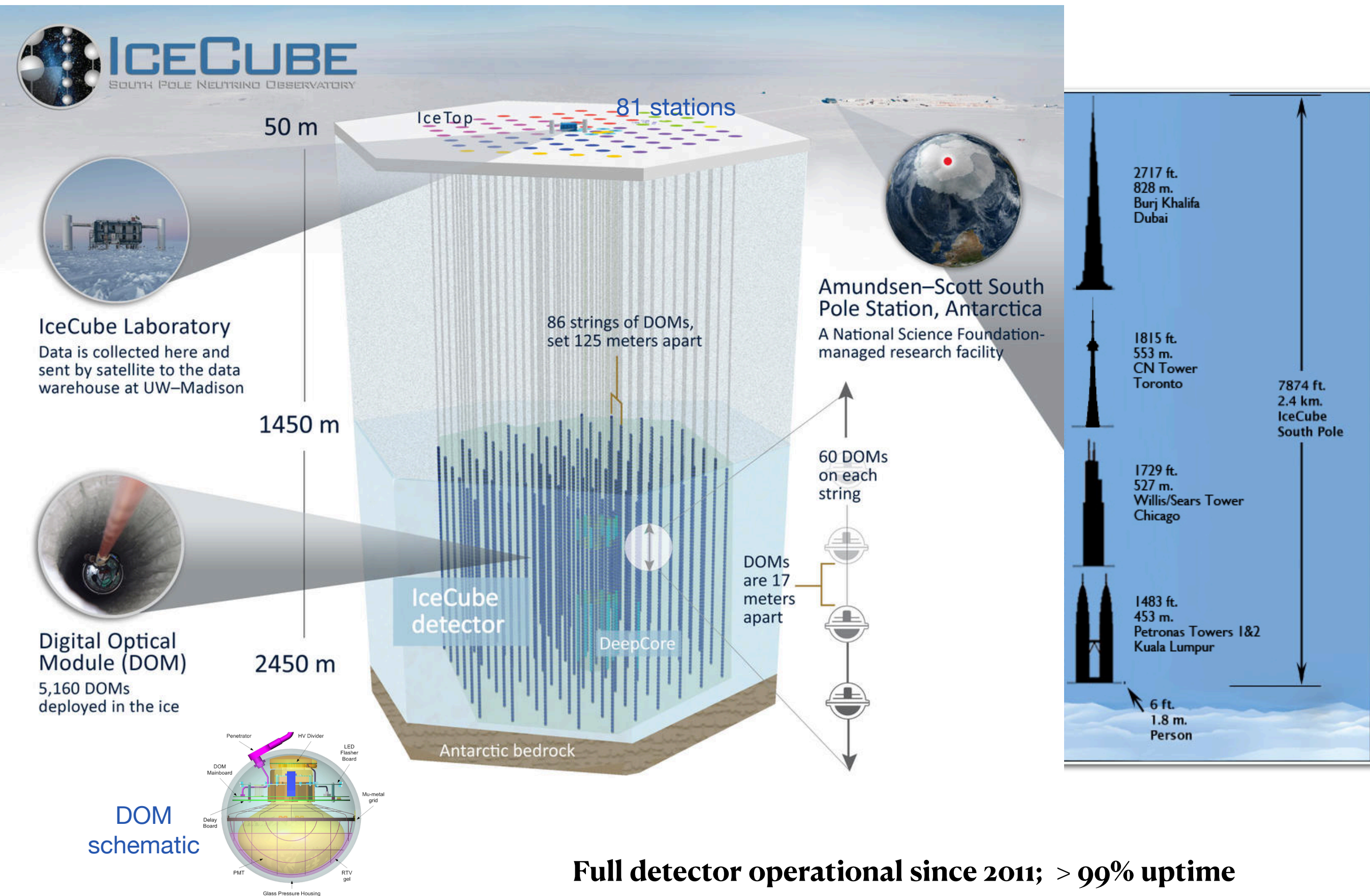


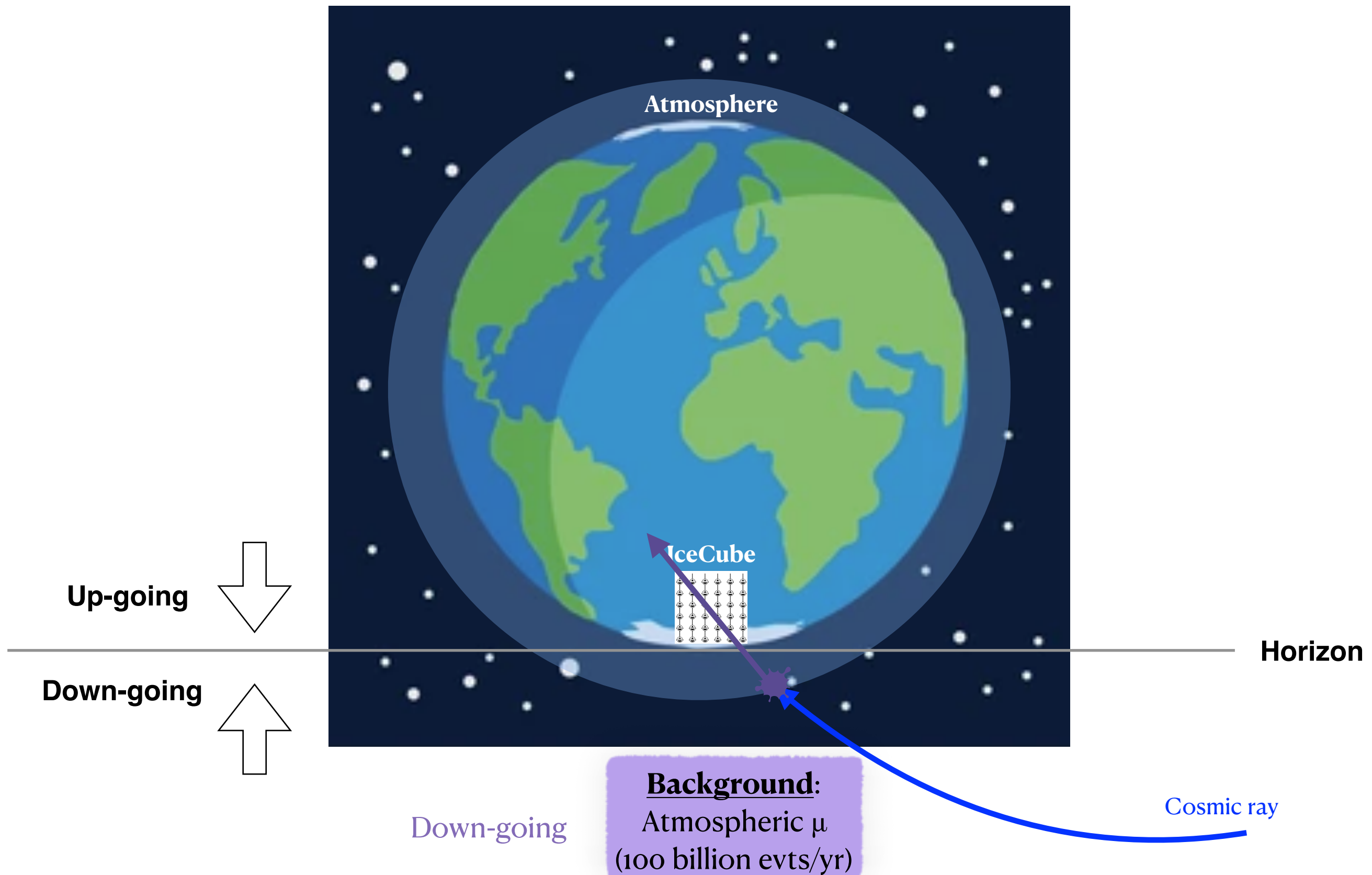
Interactions of accelerated cosmic rays simultaneously produce high energy ν and γ -rays

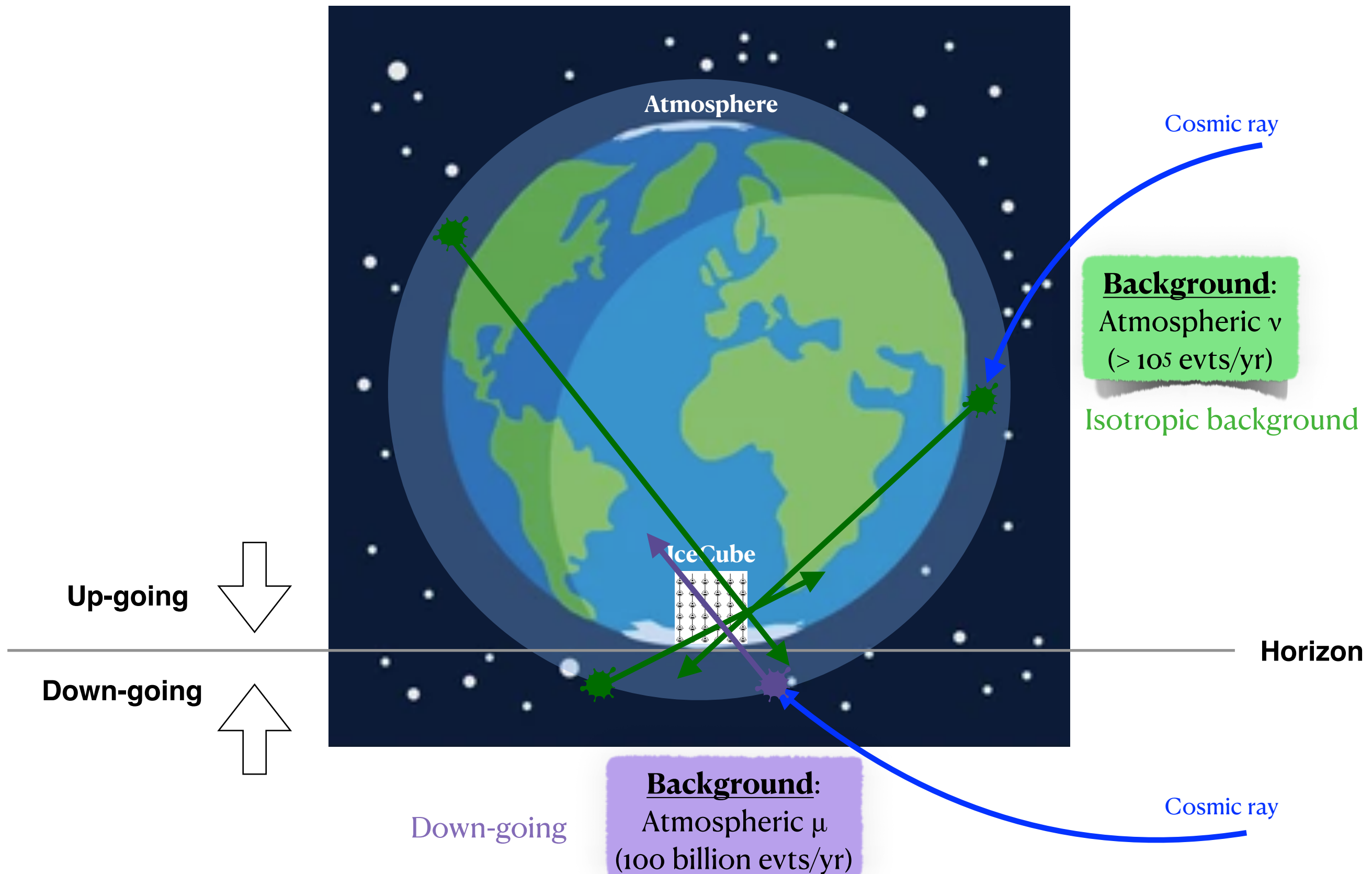
$$p + p/\gamma \rightarrow \nu + \gamma + X$$

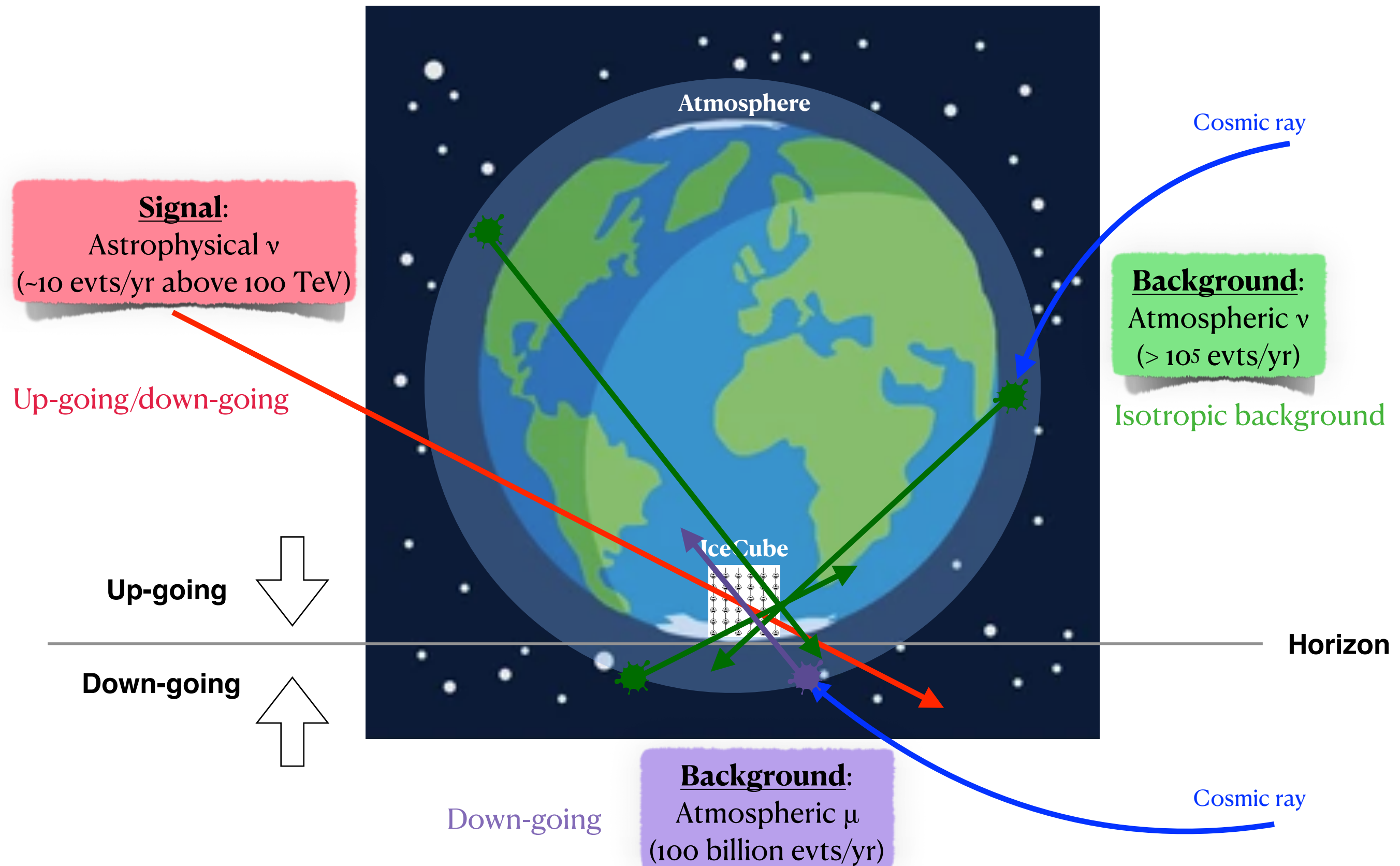


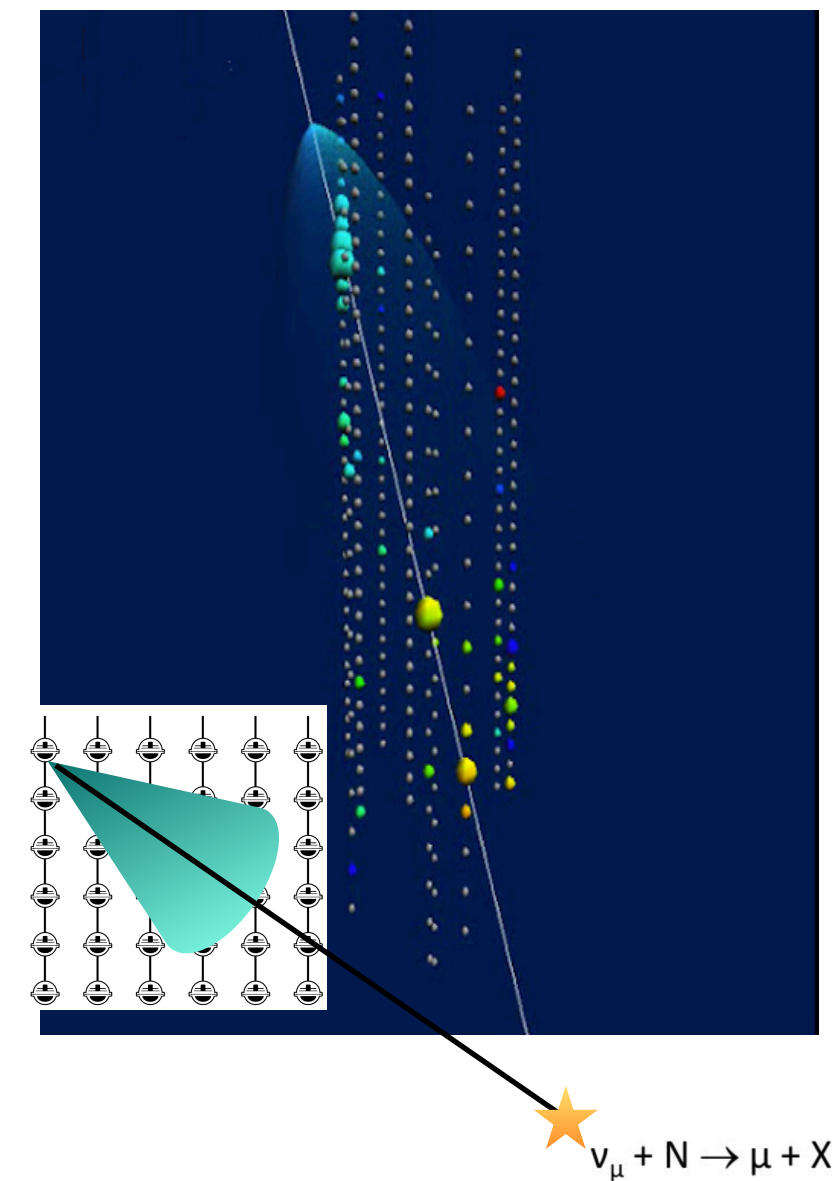
ν Neutrinos are ideal messengers to peek far into the Universe and into its most extreme environments



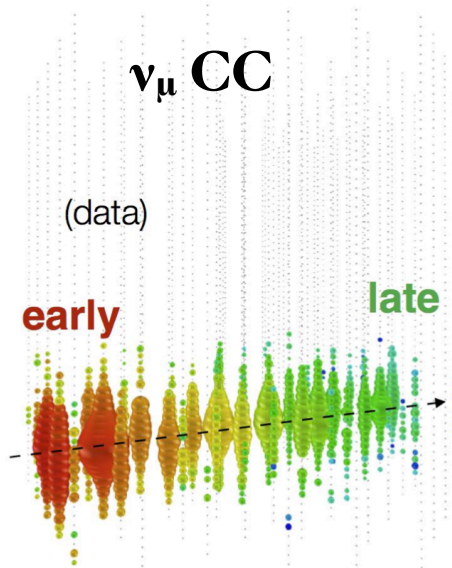
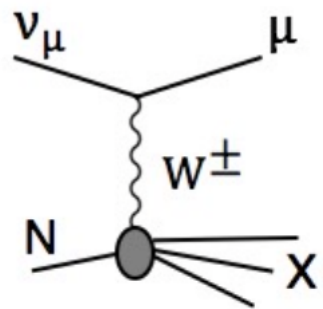






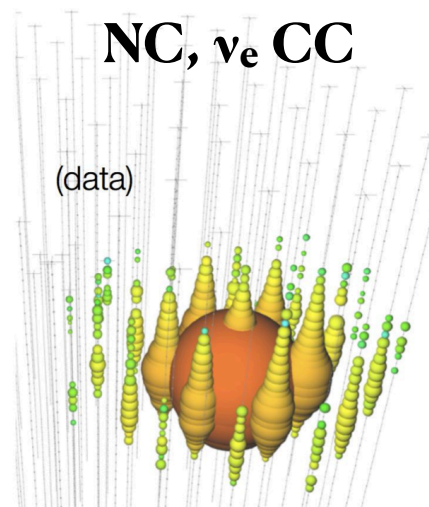
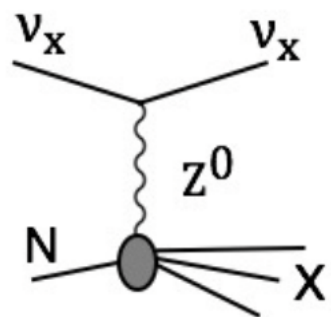


IceCube detects Cherenkov radiation from the secondary particles produced in charged-current (CC) and neutral-current (NC) interactions of neutrinos in the vicinity of the detector



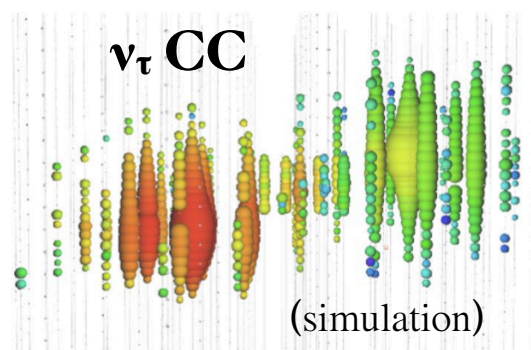
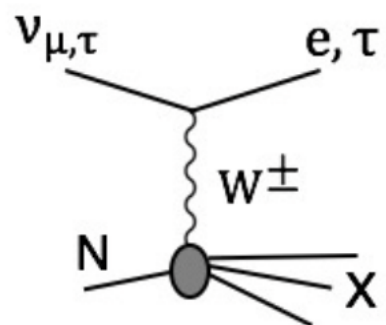
Tracks:

- Starting tracks and through-going
- Energy resolution: factor of ~ 2
- Angular resolution < 1 deg



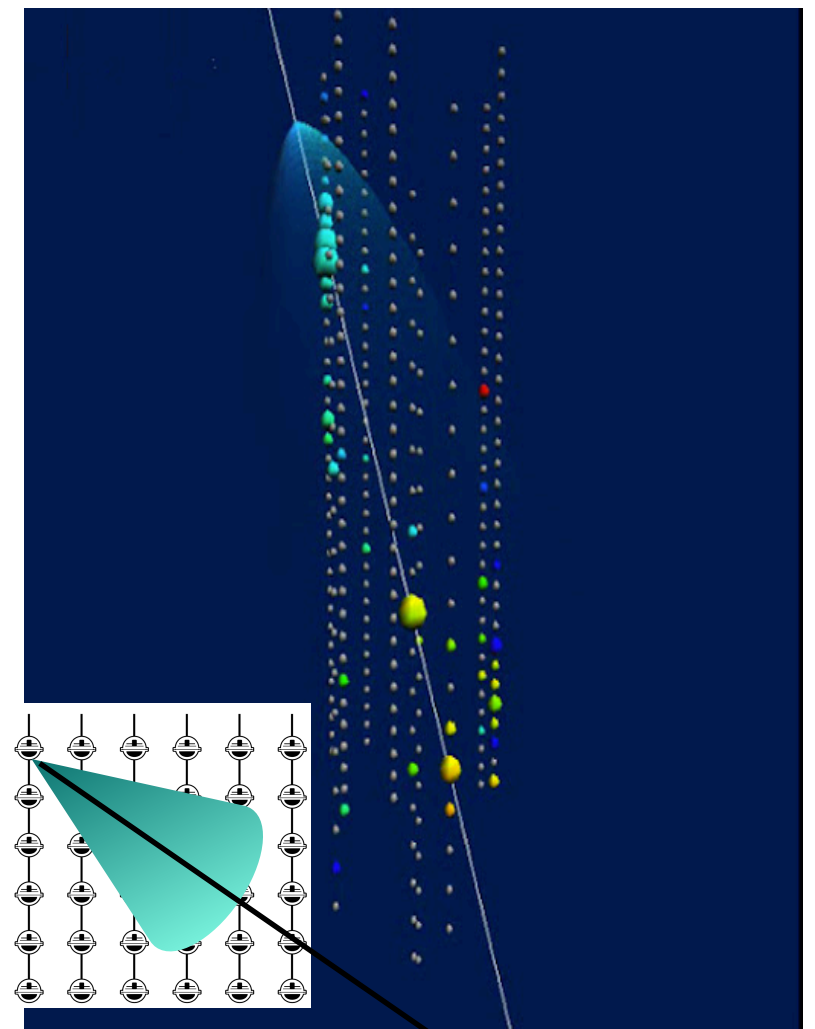
Cascades:

- EM and hadronic cascades
- Energy resolution: $\sim 10\text{-}15\%$
- Angular resolution > 10 deg



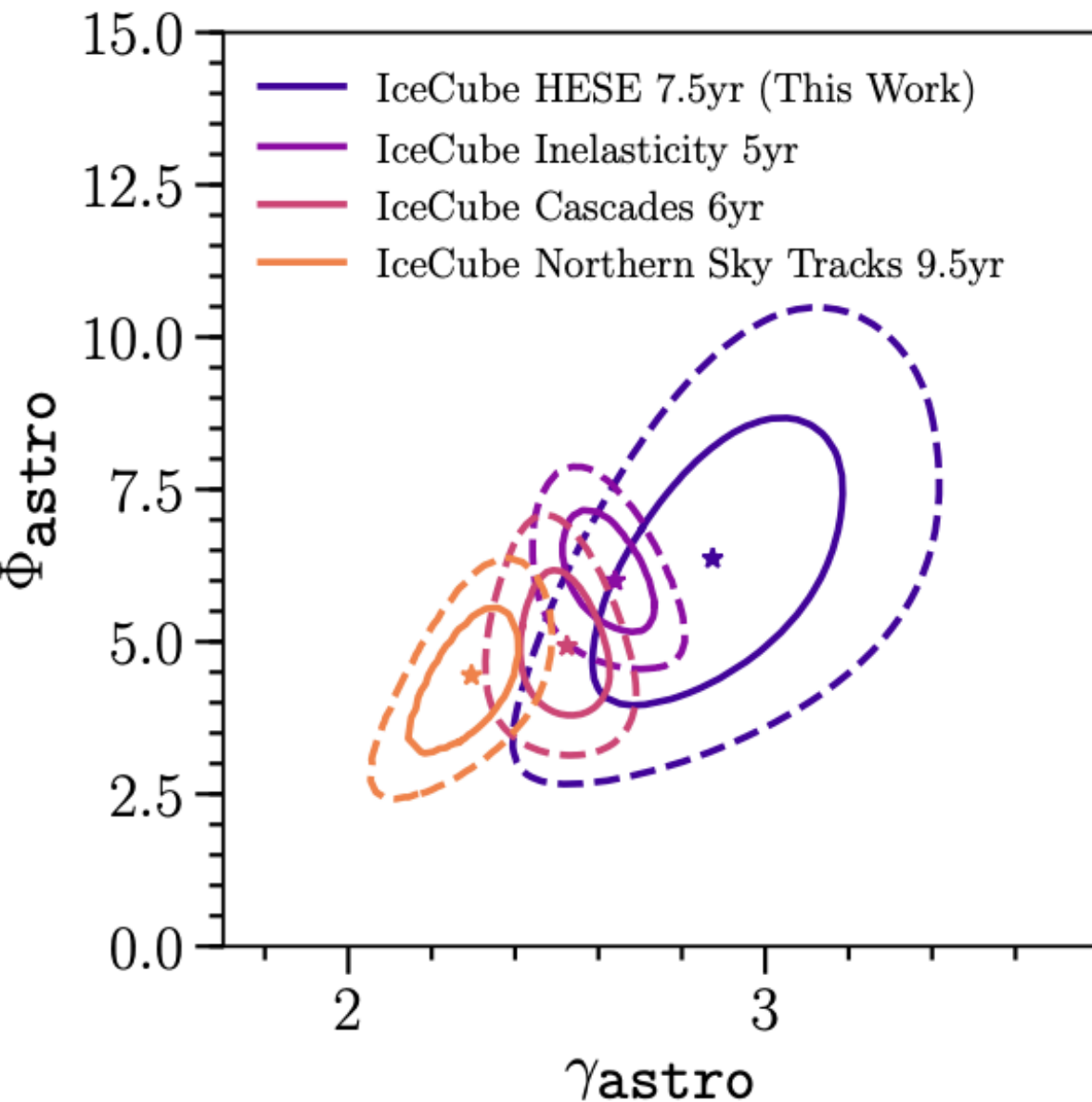
Double Cascades:

- τ hadronic decay (double bang)
- Resolvable above ~ 100 TeV



$\nu_\mu + N \rightarrow \mu + X$

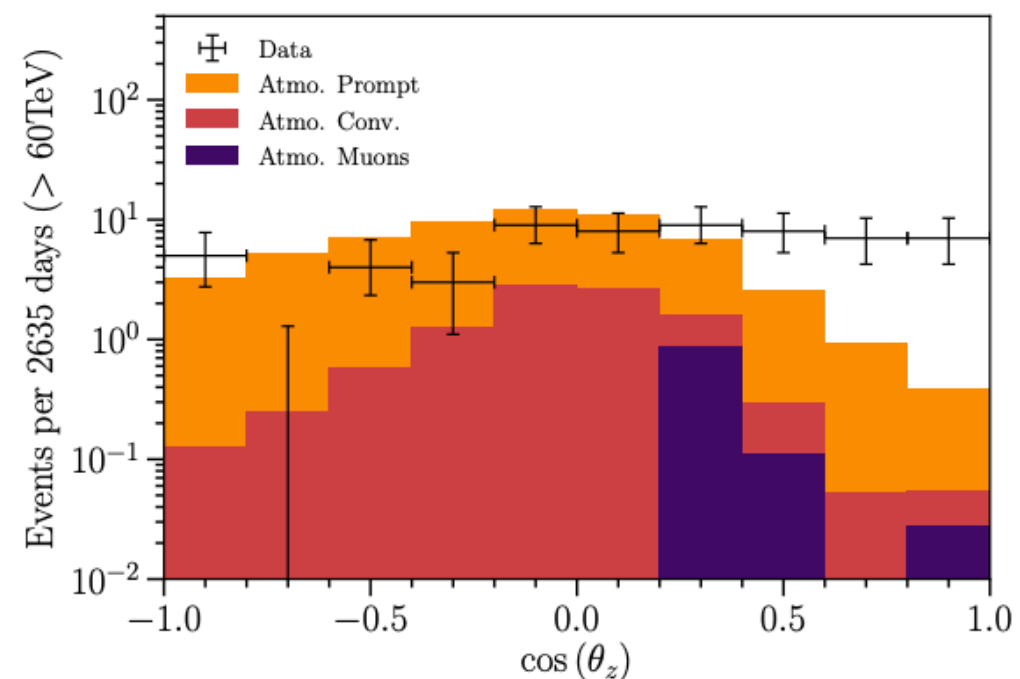
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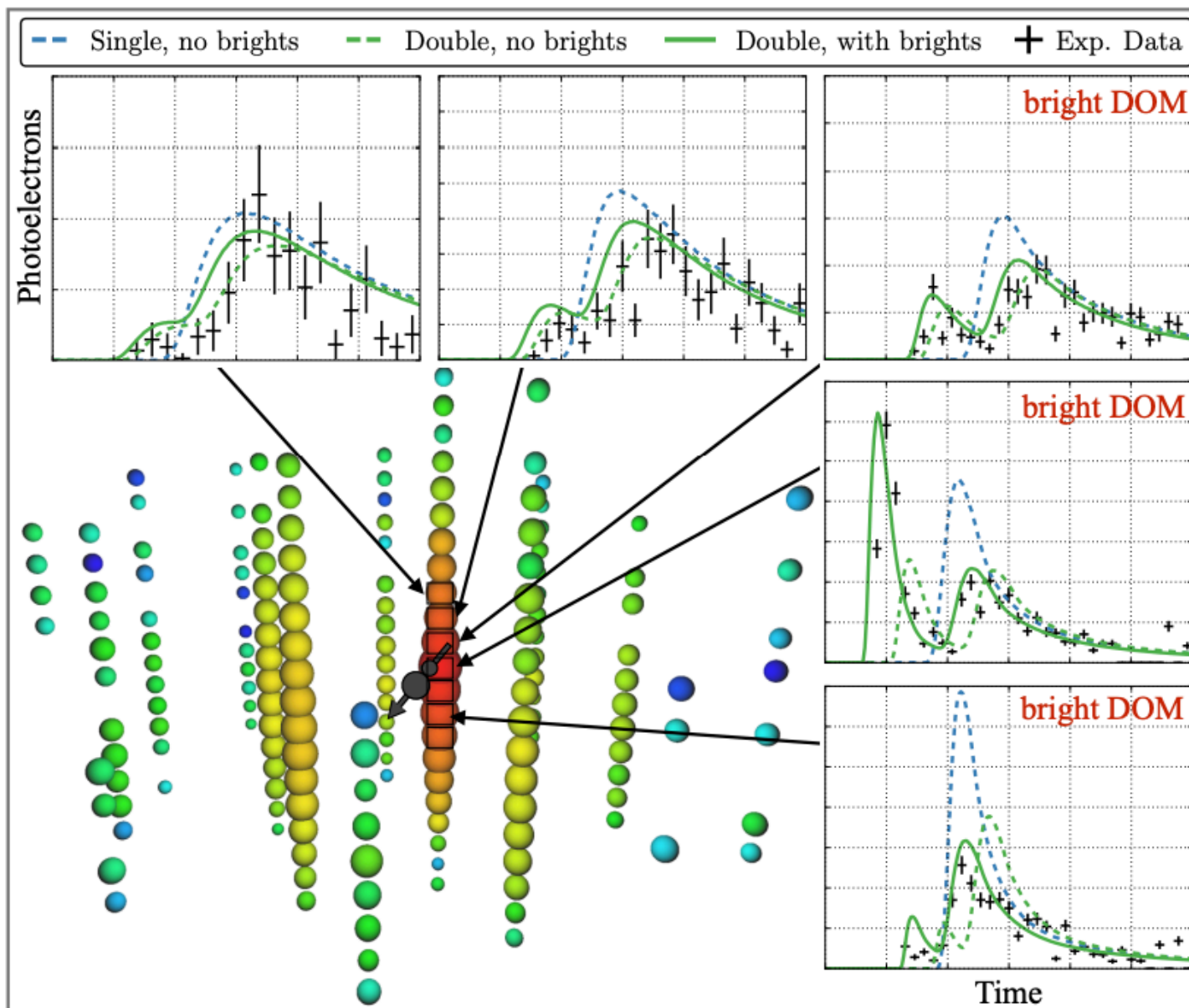


$$\Phi(E_\nu) = \Phi_{\text{astro}} \left(\frac{E_\nu}{100 \text{ TeV}} \right)^{-\gamma_{\text{astro}}}$$

Simple power-law flux assumption for the astrophysical flux

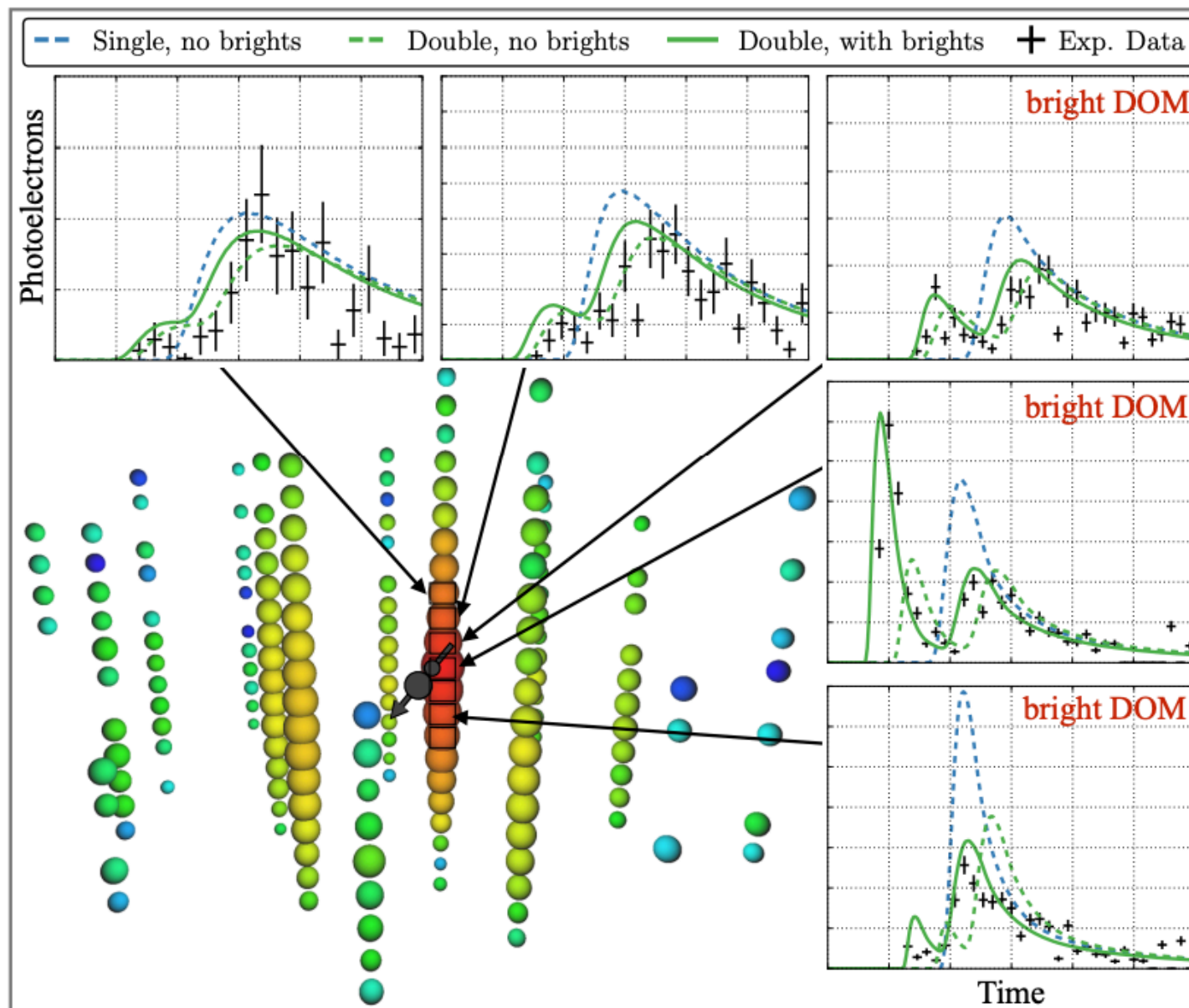
- ▶ Spectral index in the Northern hemisphere (~ 2.3) is harder than the fully-sky index measured with starting track events (~ 2.9); but non-negligible uncertainties
- ▶ No hints of additional spectral structure in the data





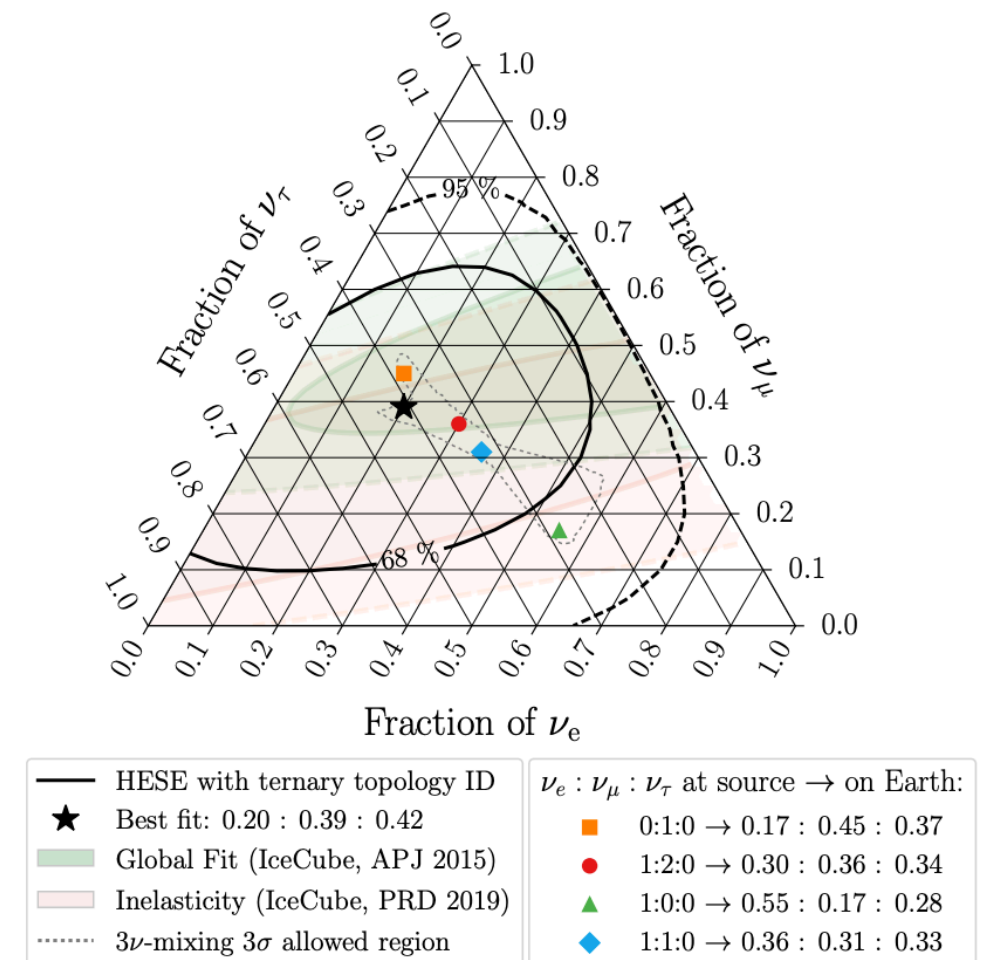
τ decay length: 50m/PeV

- 2 candidate events (above 60 TeV) in 7.5 years
- Double cascade and double pulse: shower (first-bang) + τ decay (second-bang)
- > 75% and > 97% probabilities of being astrophysical τ respectively



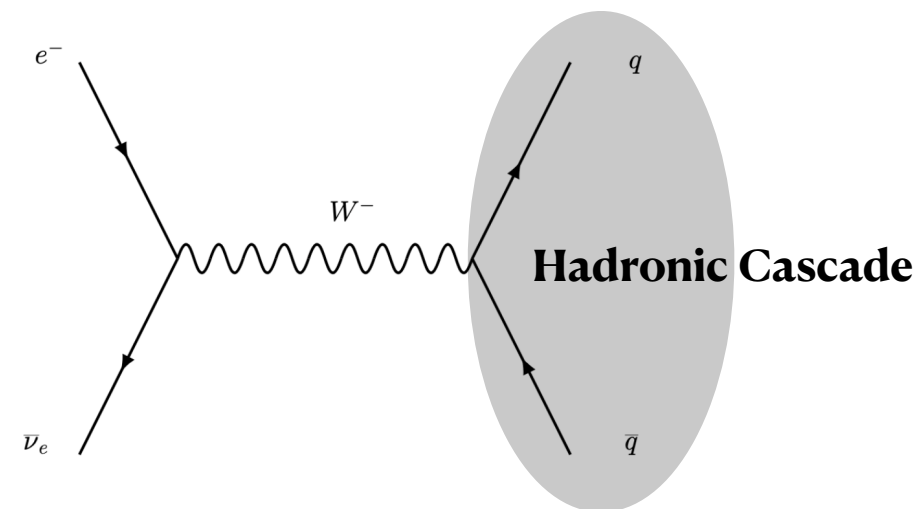
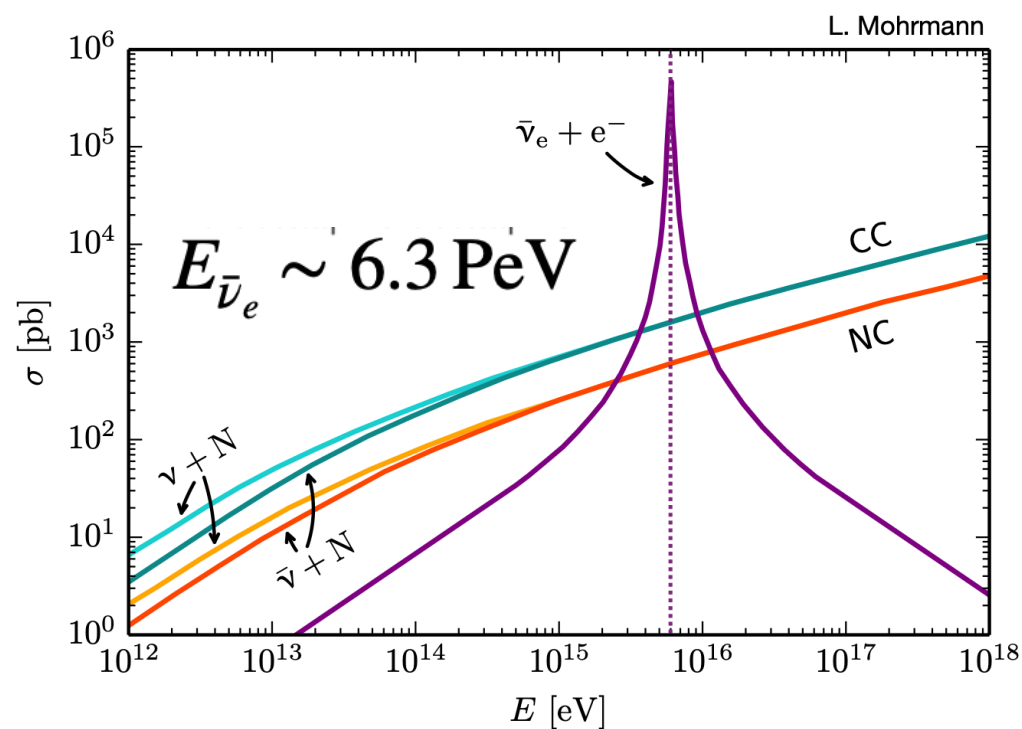
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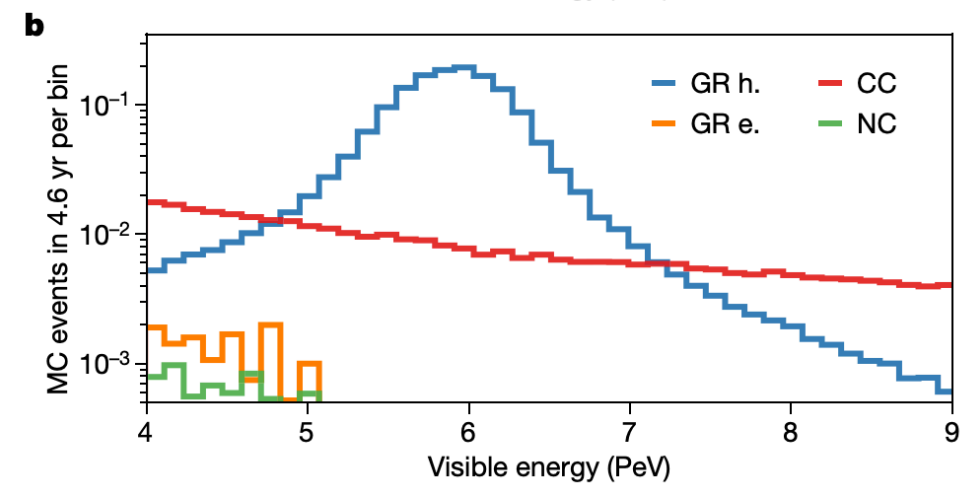
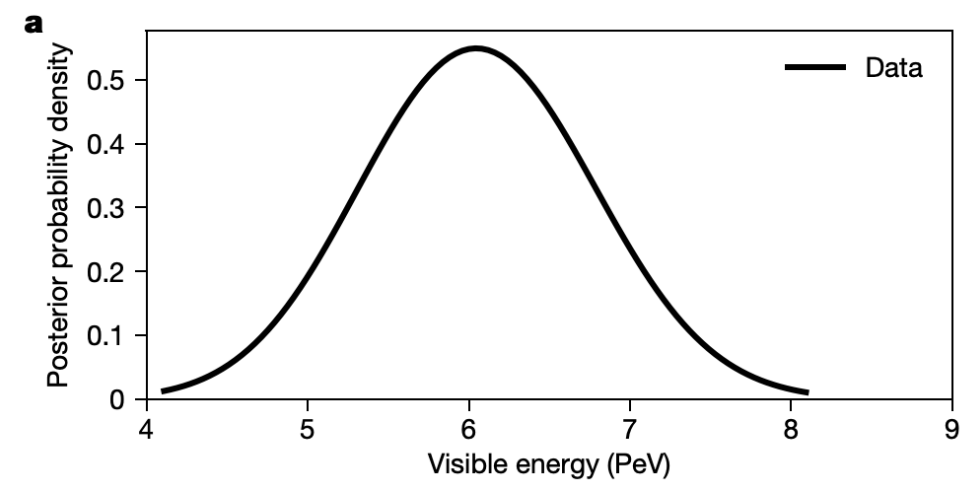
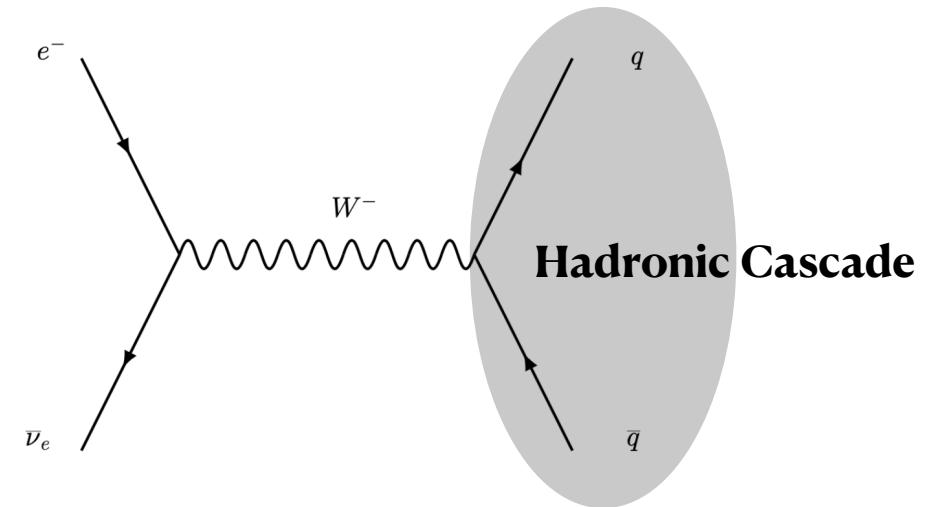
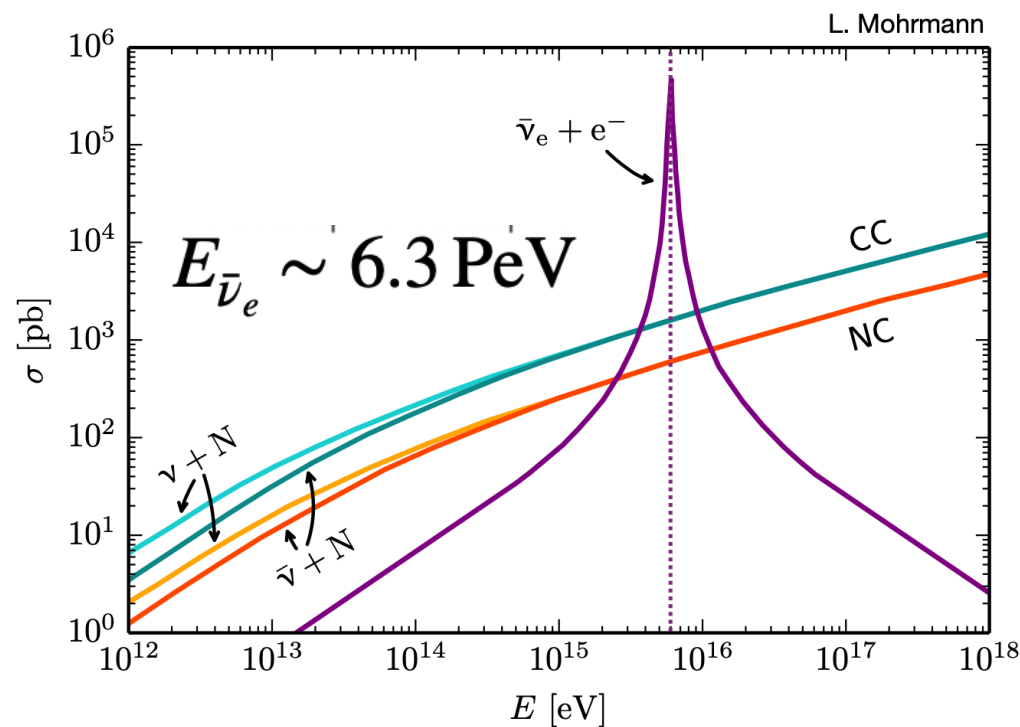


Data consistent with flavour equipartition

Resonant formation of a W^- : $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow X$



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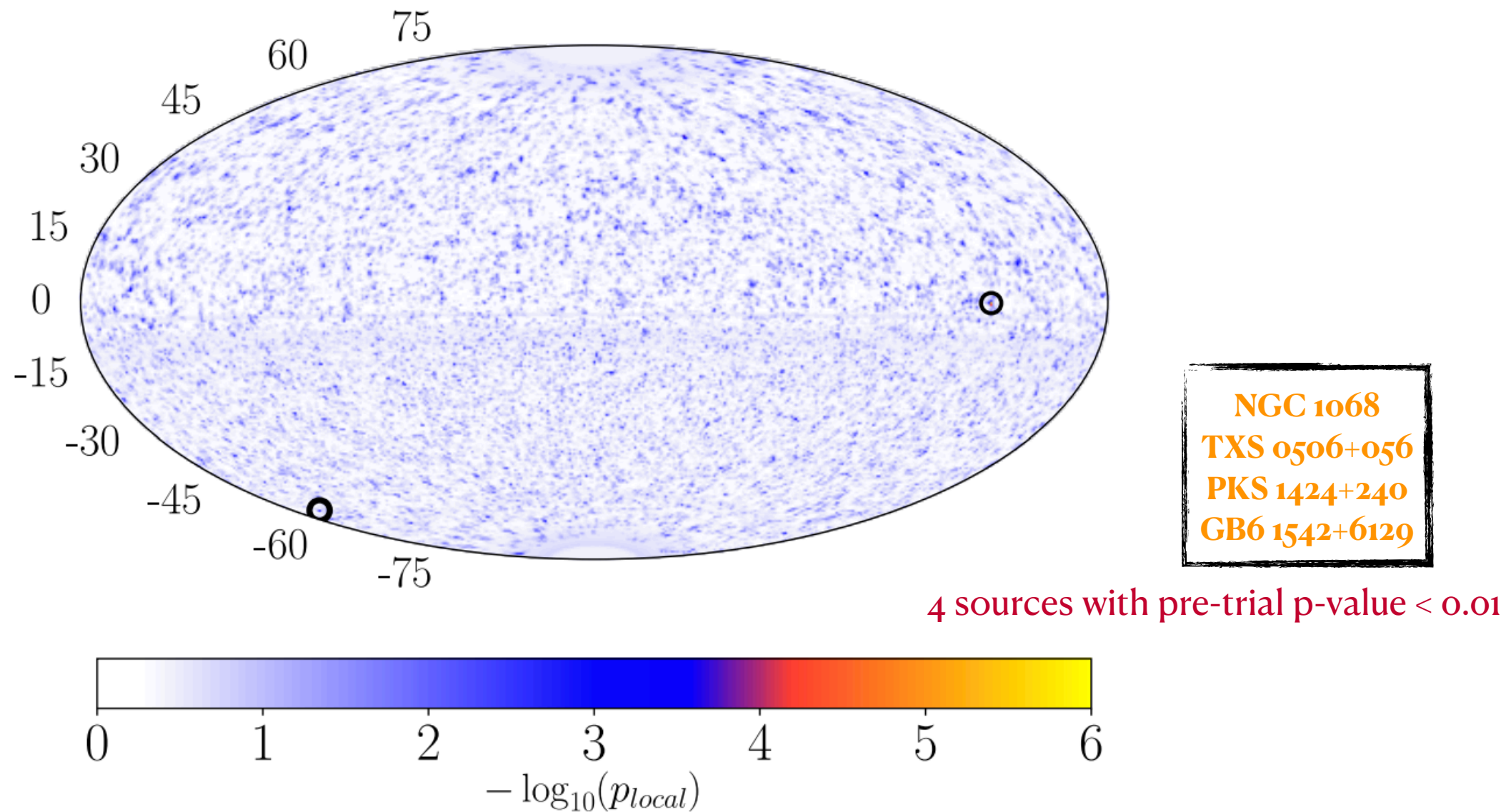


First Glashow resonance candidate in IceCube @ $E \sim 6 \text{ PeV}$

- New analysis has an increased sensitivity to PeV cascades
- Allows disentangling of neutrinos and anti-neutrinos!

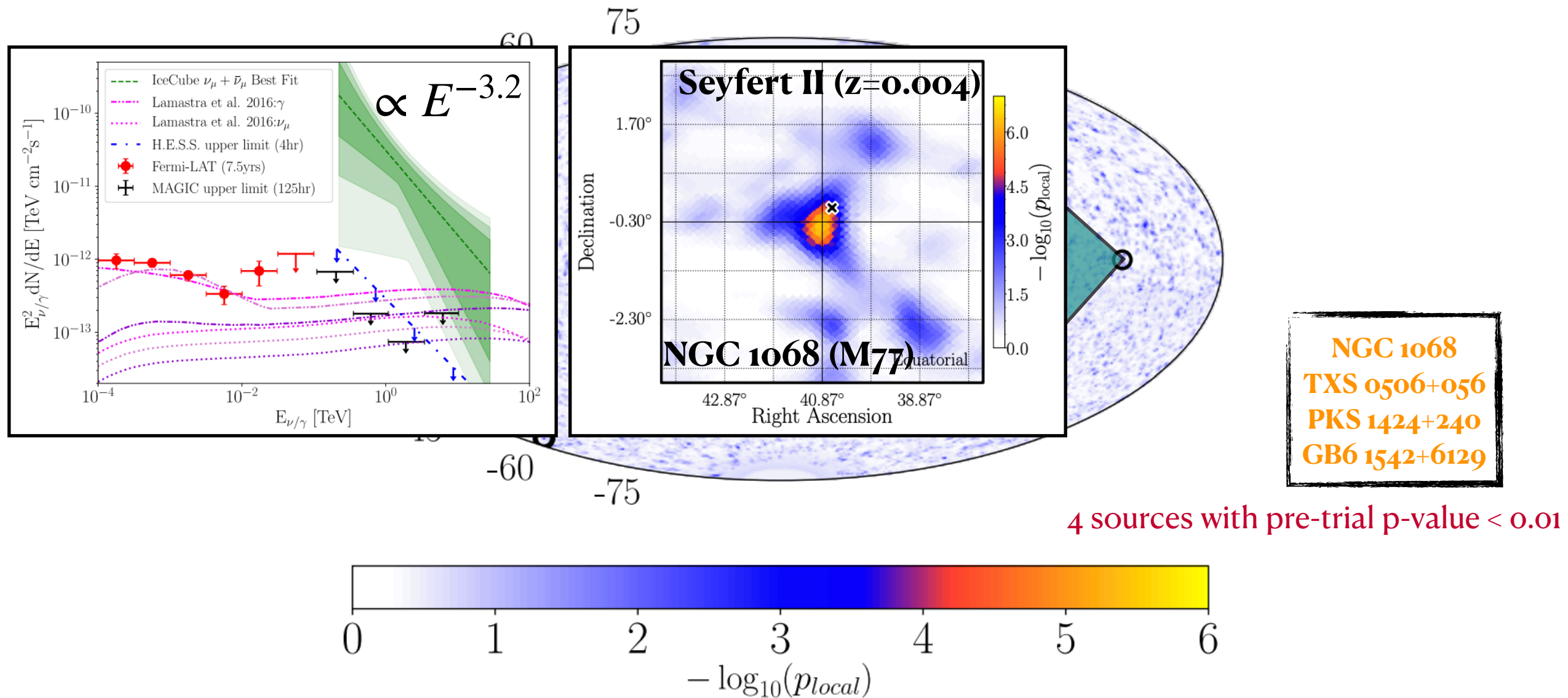
Nature 591 (2021) 220–224

All-sky scan to search for self-clusterings of neutrinos in 10 year IceCube data



- Northern source catalog search inconsistent with background at 3.3σ ; might hint at correlations with observed neutrinos

All-sky scan to search for self-clusterings of neutrinos in 10 year IceCube data



- Northern source catalog search inconsistent with background at 3.3σ ; might hint at correlations with observed neutrinos
- Most significant Northern sky hotspot coincident with **NGC 1068**; at 2.9σ above bkgd (post-trial)

RESEARCH

RESEARCH ARTICLE SUMMARY

NEUTRINO ASTROPHYSICS

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

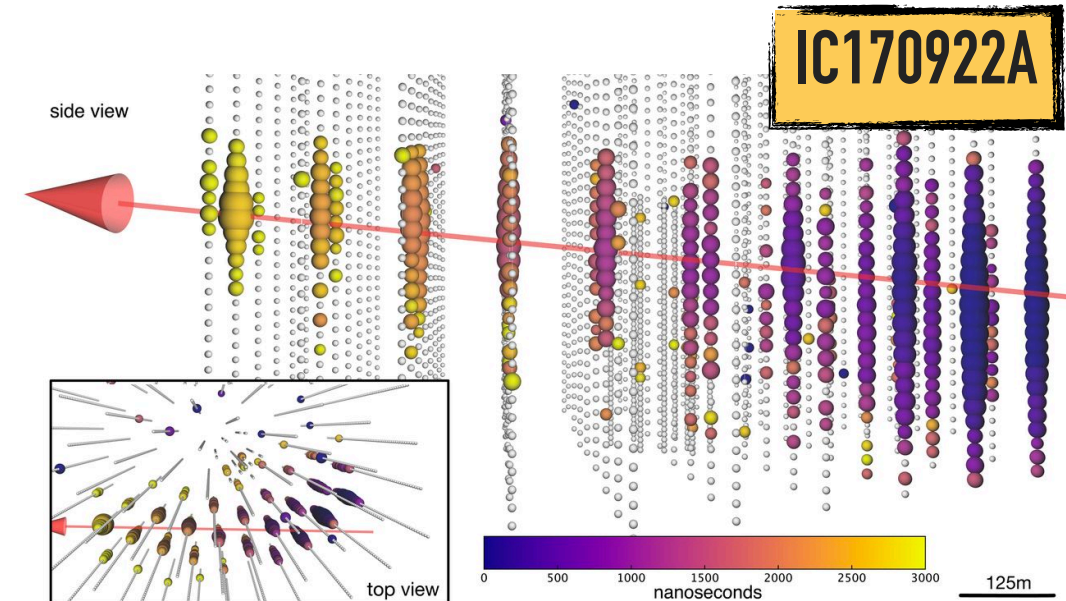
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift*/*NuSTAR*, VERITAS, and VLA/17B-403 teams*†

trinos, IceCube provides real-time triggers for observatories around the world measuring γ -rays, x-rays, optical, radio, and gravitational waves, allowing for the potential identification of even rapidly fading sources.

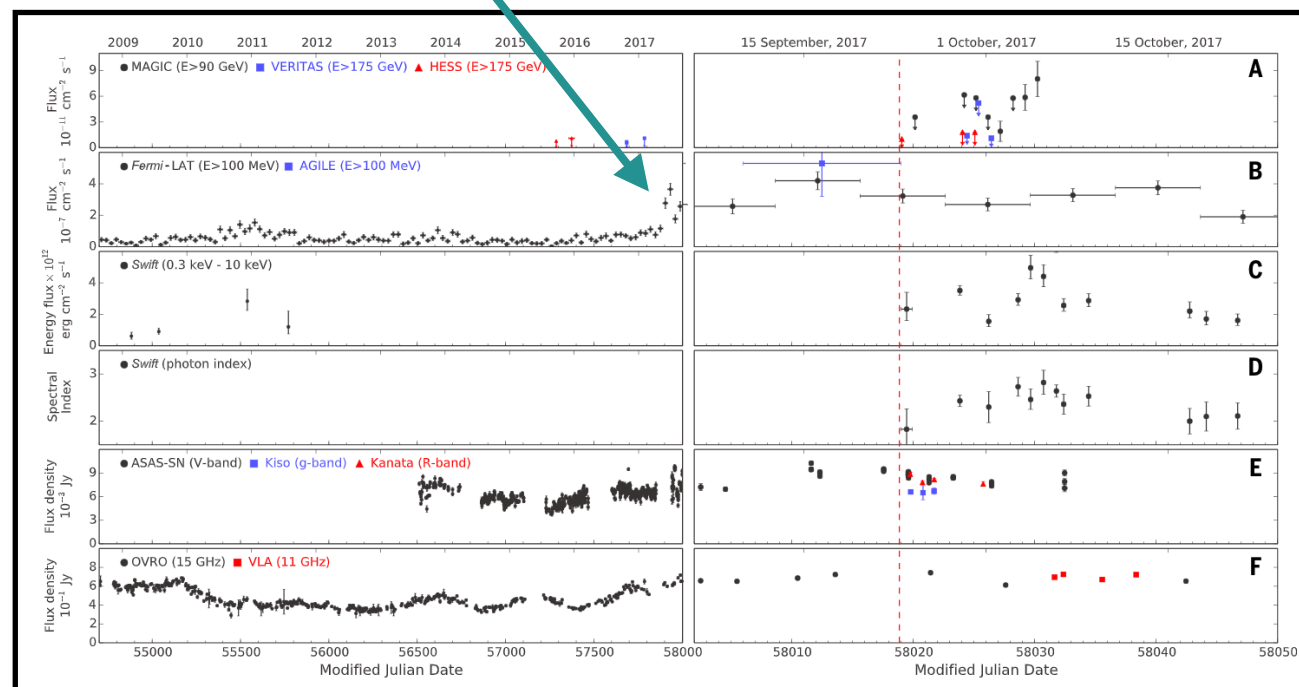
RESULTS: A high-energy neutrino-induced muon track was detected on 22 September 2017, automatically generating an alert that was distributed worldwide within 1 min of detection and prompted follow-up searches by telescopes over a broad range of wavelengths. On 28 September 2017, the *Fermi* Large Area Telescope Collaboration reported that the di-

ON OUR WEBSITE

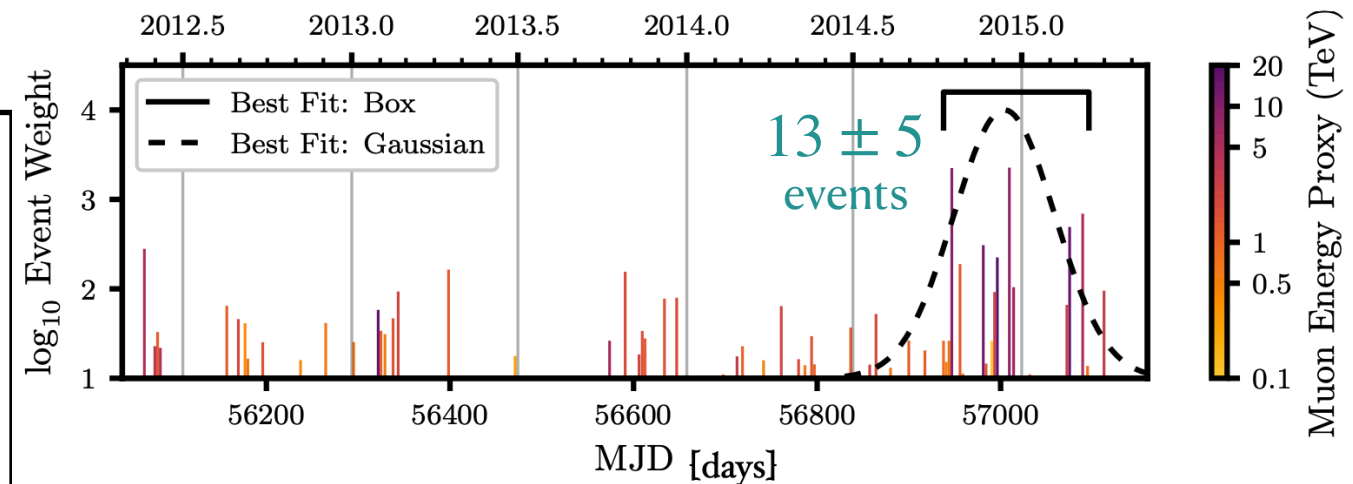
Read the full article at <http://dx.doi.org/10.1126/science.aat1378>



- ▶ ~290 TeV neutrino from the direction of blazar TXS 0506+056 ($z=0.336$)
- ▶ Observed by MAGIC and Fermi in increased activity (flaring) state in the following days



Analysis of archival IceCube data confirmed a 3.5σ excess over ~110 days in 2014-15



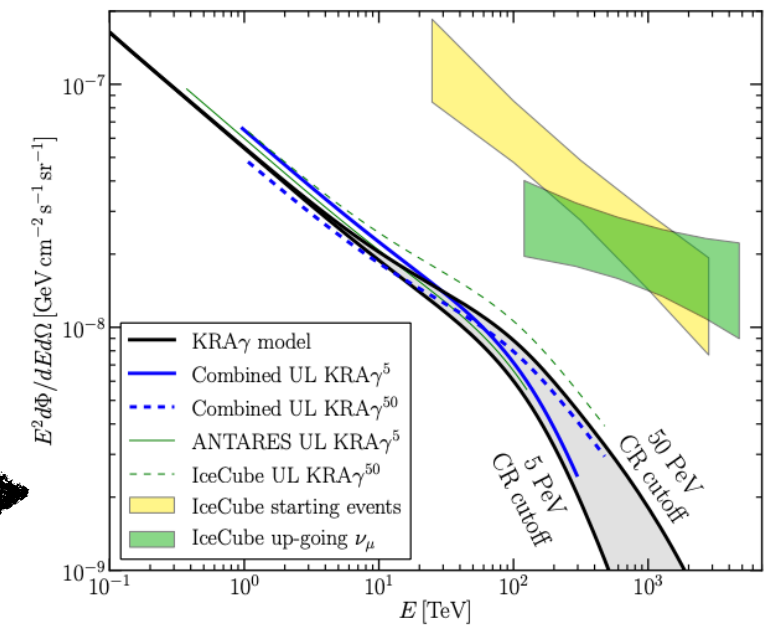
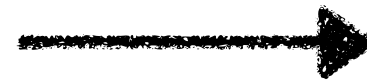
First successful multi-messenger follow-up campaign for a real-time alert!

IceCube [Science, Vol. 361 (2018) 6398]

IceCube++ [Science, Vol. 361 (2018) 6398]

TeV γ -ray sources and PeV cosmic rays in the galaxy hint at possible hadronic processes and a subsequent diffuse Galactic neutrino flux

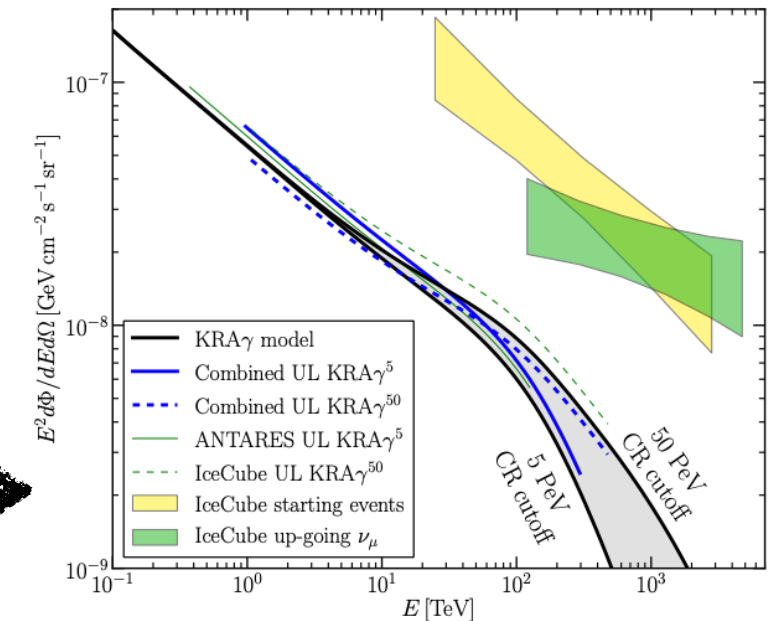
Galactic contribution to diffuse ν flux already constrained by IceCube to $\sim 10\%$ ($E > 1$ TeV)



IceCube+ [ApJ 868 (2018) 2]

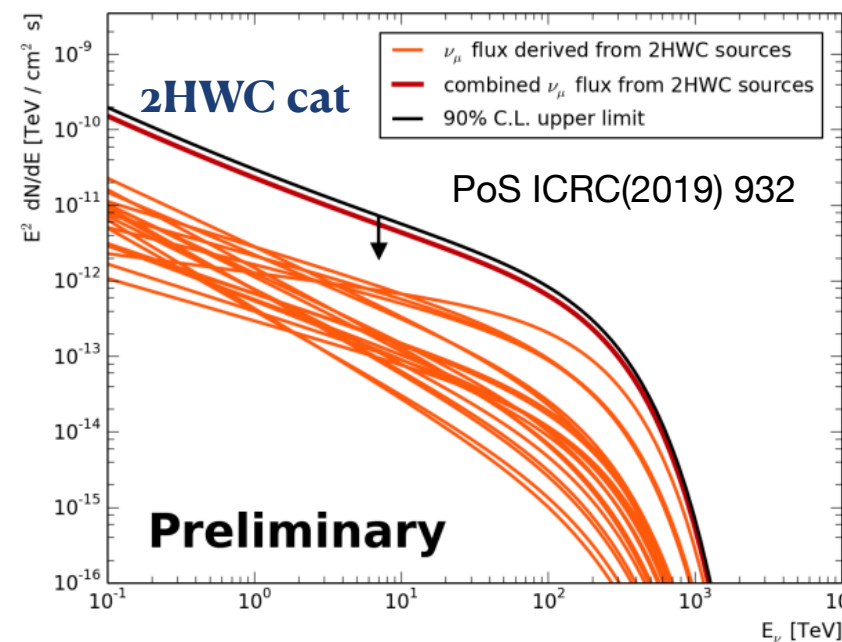
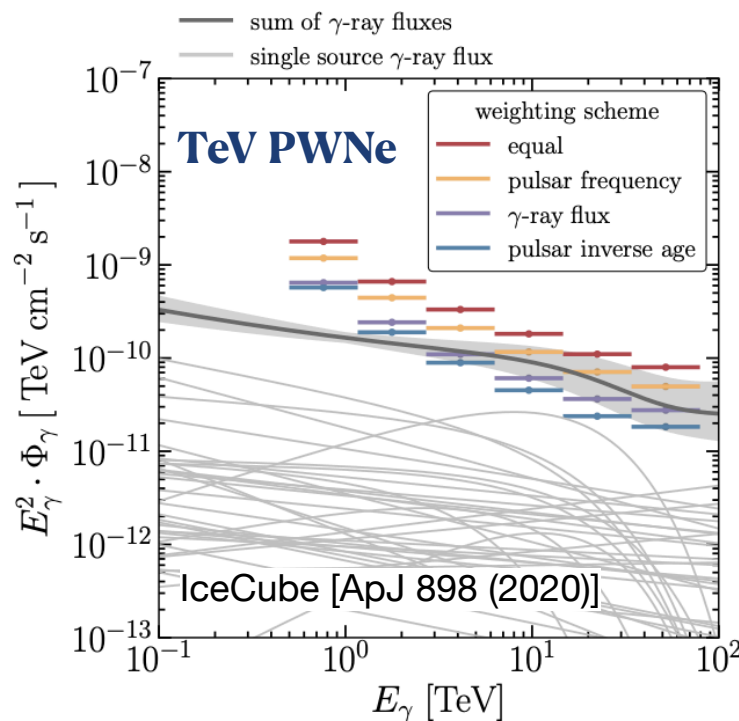
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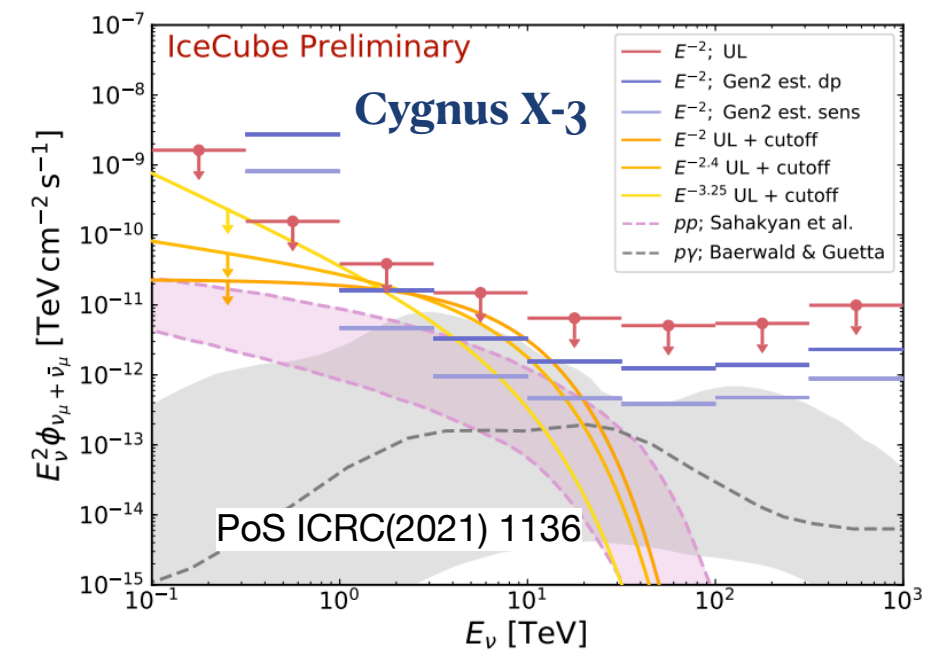


IceCube+ [ApJ 868 (2018) 2]

Recent stacking searches with Galactic source catalogs show no strong correlation with extended or point sources



Strong individual source upper limits!



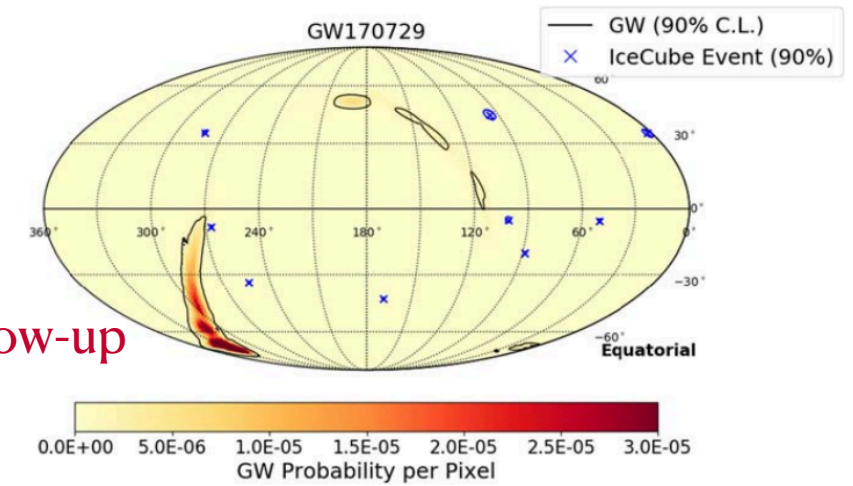
However, few local hotspots ($< 3\sigma$) identified: **Cygnus X-3, MGRO 1908+06, RX J1713.7-3946**

Multi-messenger searches:

Multi-wavelength connections:

- **Radio AGN** [PoS ICRC(2021) 949]
- **ULIRGs** [PoS ICRC(2021) 1115]
- **X-ray AGN** [PoS ICRC(2021) 1142]
- **VHE Gamma with alerts** [PoS ICRC(2021) 960]

GW follow-up



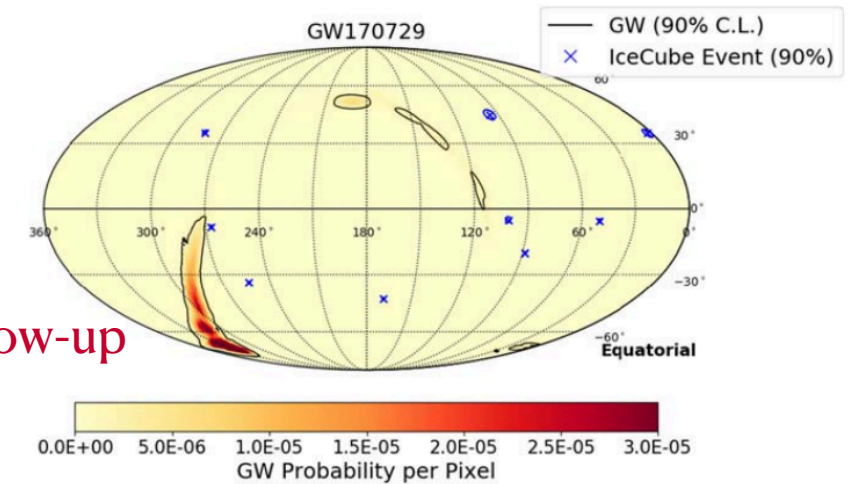
[IceCube ApJL 898 (2020) 1]

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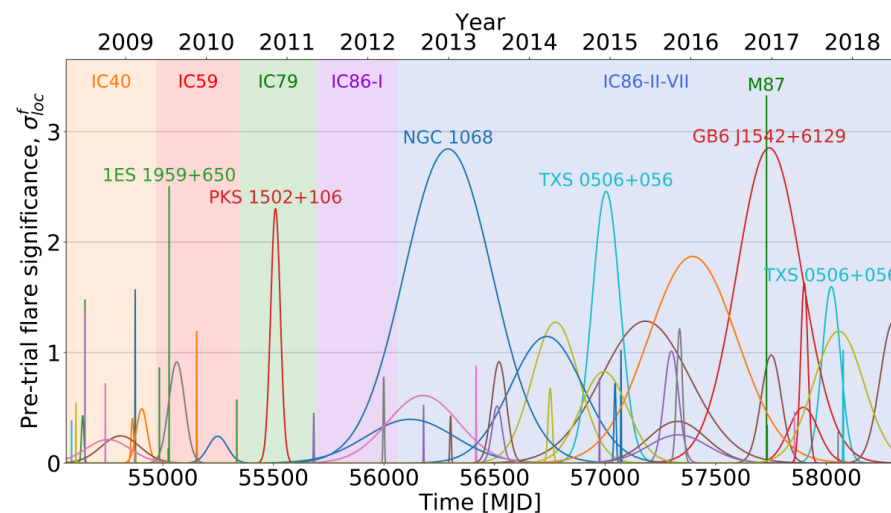
- **Radio AGN** [PoS ICRC(2021) 949]
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GW follow-up

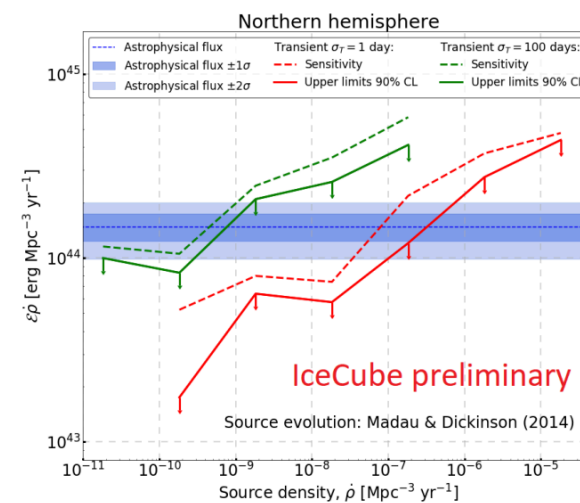


[IceCube ApJL 898 (2020) 1]

Time-dependent/multi-flare searches: all-sky scan and source catalog search



[IceCube ApJL 920 L45 (2021)]



[PoS ICRC(2021) 1128]

Transients:

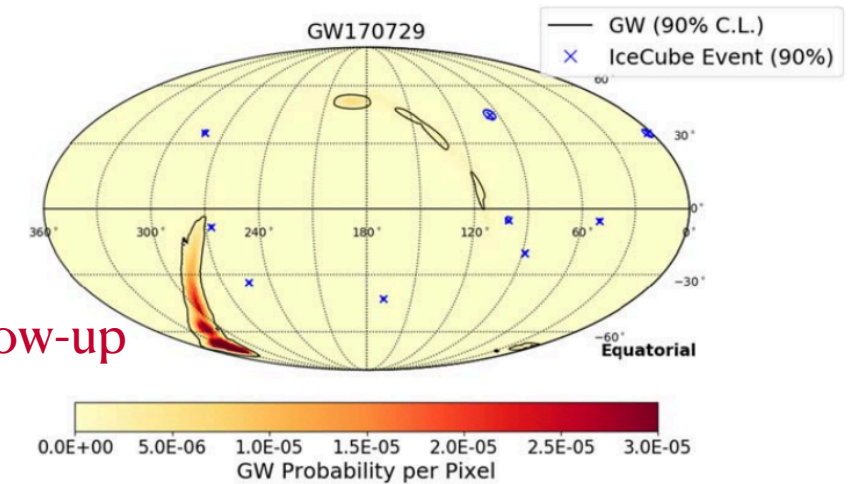
- **GRBs** [PoS ICRC(2021) 1118]
- **sub-TeV transients** [arXiv:2011.05096]

Multi-messenger searches:

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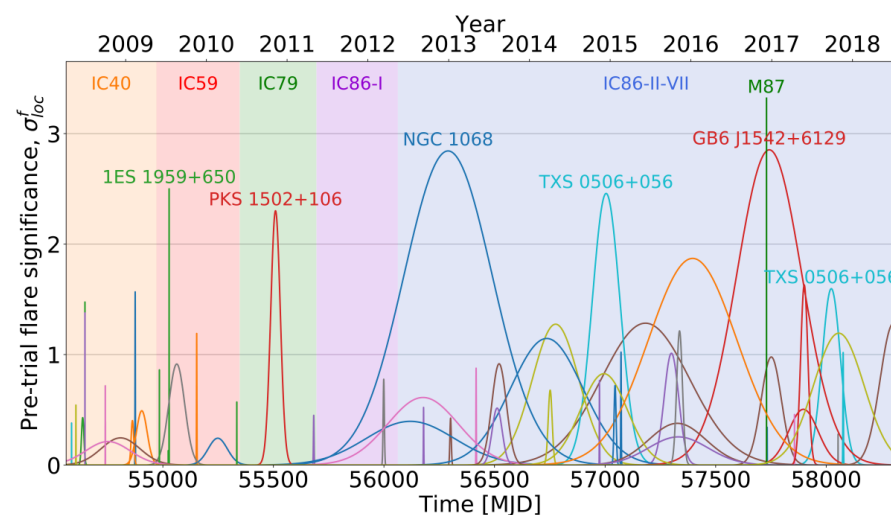
- **Radio AGN** [PoS ICRC(2021) 949]
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- **X-ray AGN** [PoS ICRC(2021) 1142]
- **VHE Gamma with alerts** [PoS ICRC(2021) 960]

GW follow-up

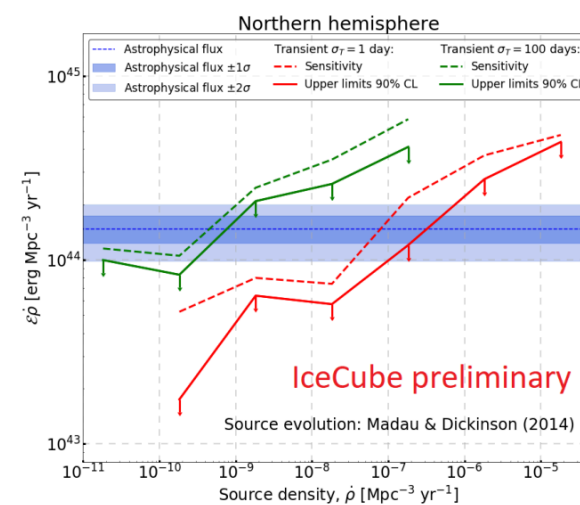


[IceCube ApJL 898 (2020) 1]

Time-dependent/multi-flare searches: all-sky scan and source catalog search



[IceCube ApJL 920 L45 (2021)]



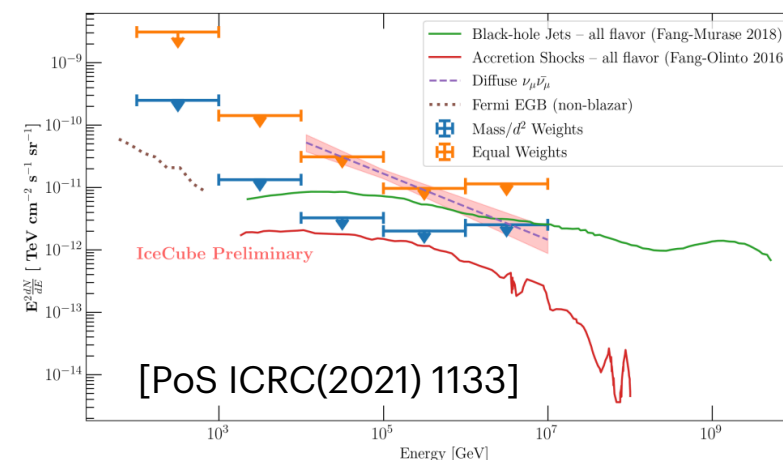
[PoS ICRC(2021) 1128]

Transients:

- **GRBs** [PoS ICRC(2021) 1118]
- **sub-TeV transients** [arXiv:2011.05096]

Galactic:

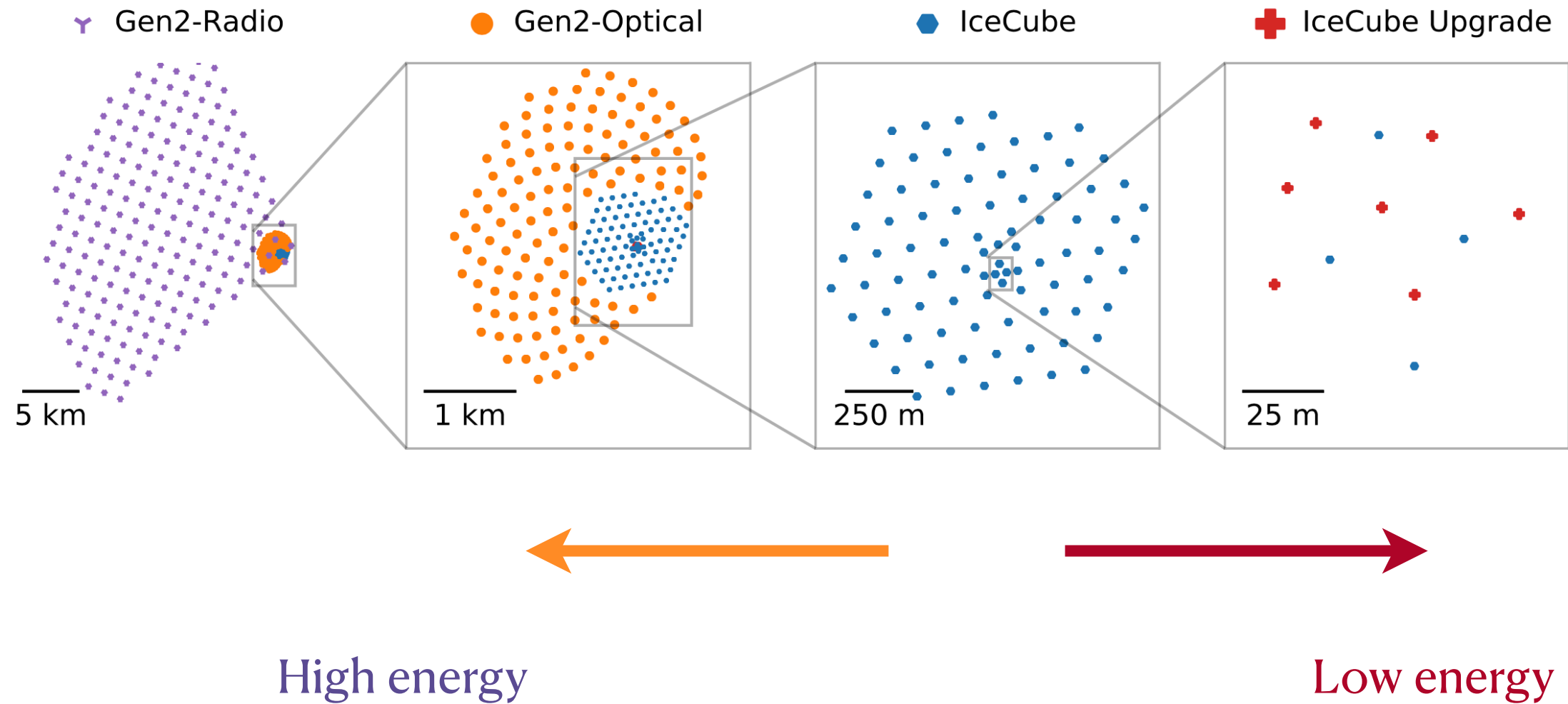
- **X-ray binaries** [PoS ICRC(2021) 1136]
- **Magnetars** [PoS ICRC(2021) 1135]

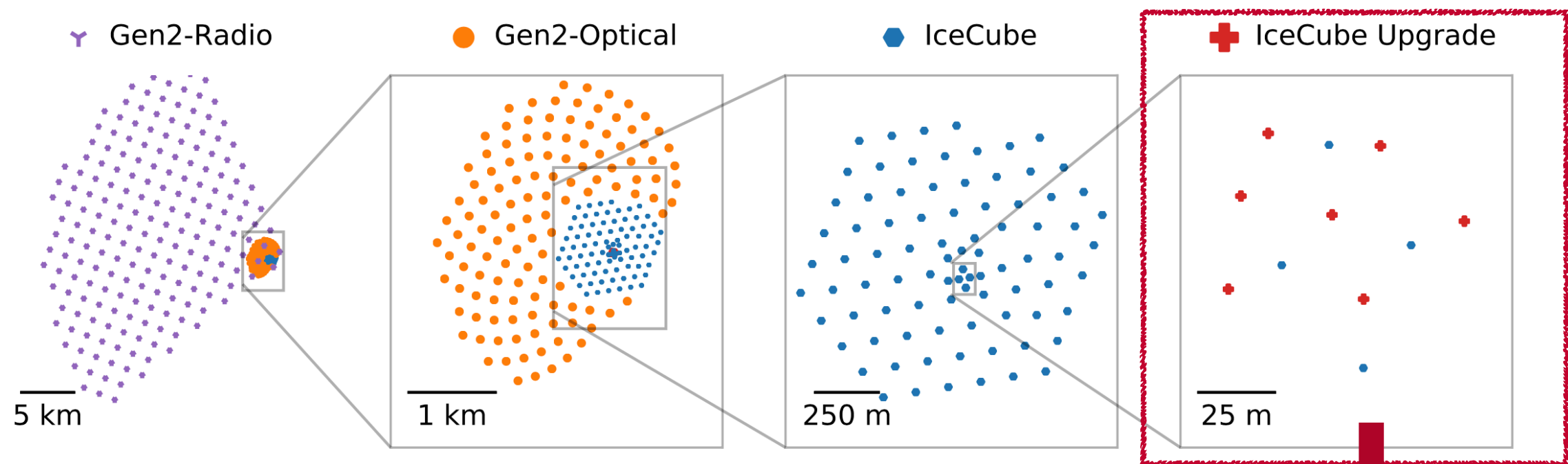


[PoS ICRC(2021) 1133]

Galaxy clusters

and many more....





High energy

- Approved and funded (construction in 2022-23)
- 7 closely-spaced strings at the bottom-centre of the detector
- New calibration devices to study ice properties and detector response
- Precision measurement of neutrino oscillations
- New DOM designs to be tested

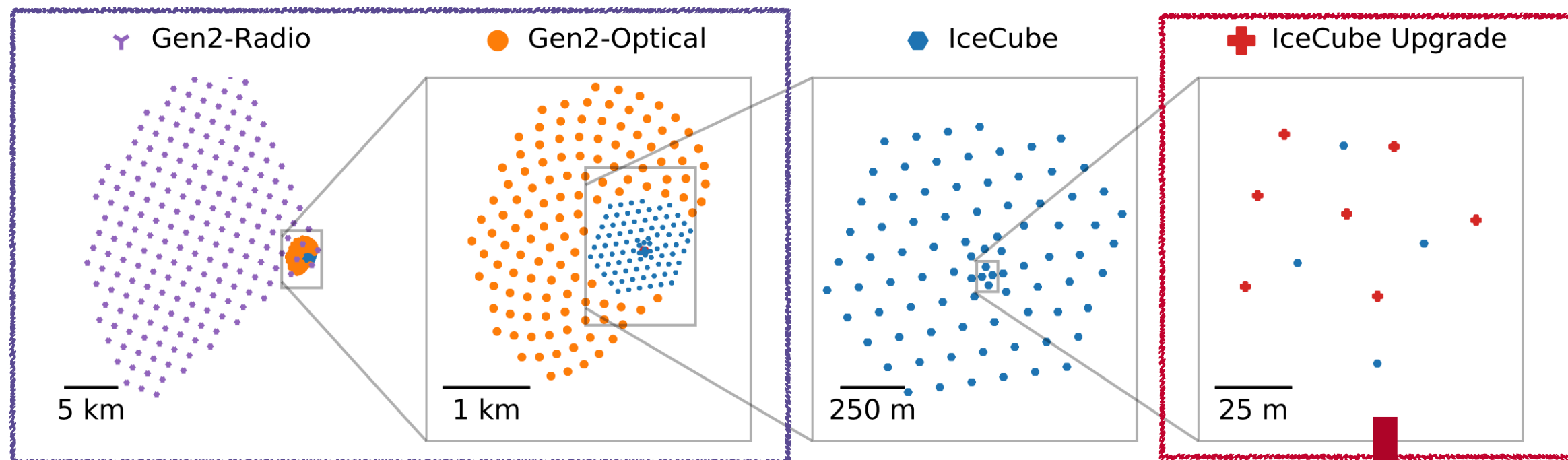


m-DOM

D-Egg



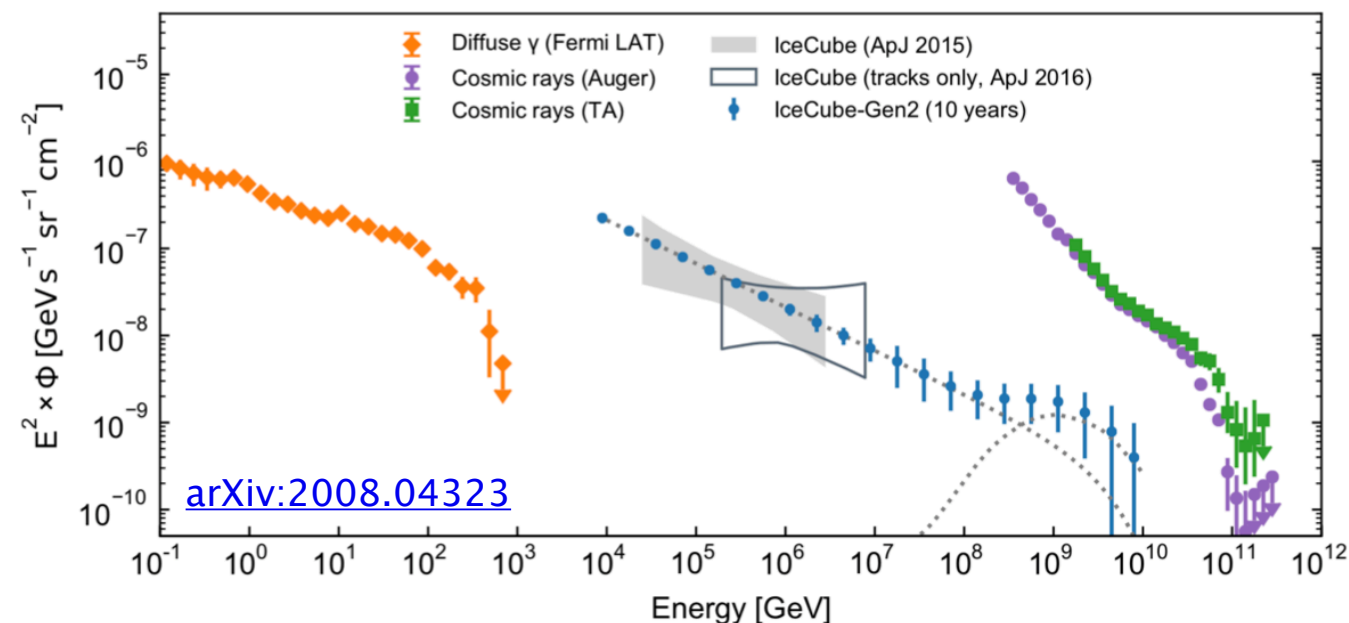
PoS ICRC(2019) 1031



IceCube Gen-2 promises to increase sensitivity by a factor ~ 10 , and extend our reach to UHE ν sky by combining optical and radio detection elements

Proposed: Gen-2 Optical: 8 km²; Gen-2 radio: 500 km²

- Approved and funded (construction in 2022-23)
- 7 closely-spaced strings at the bottom-centre of the detector
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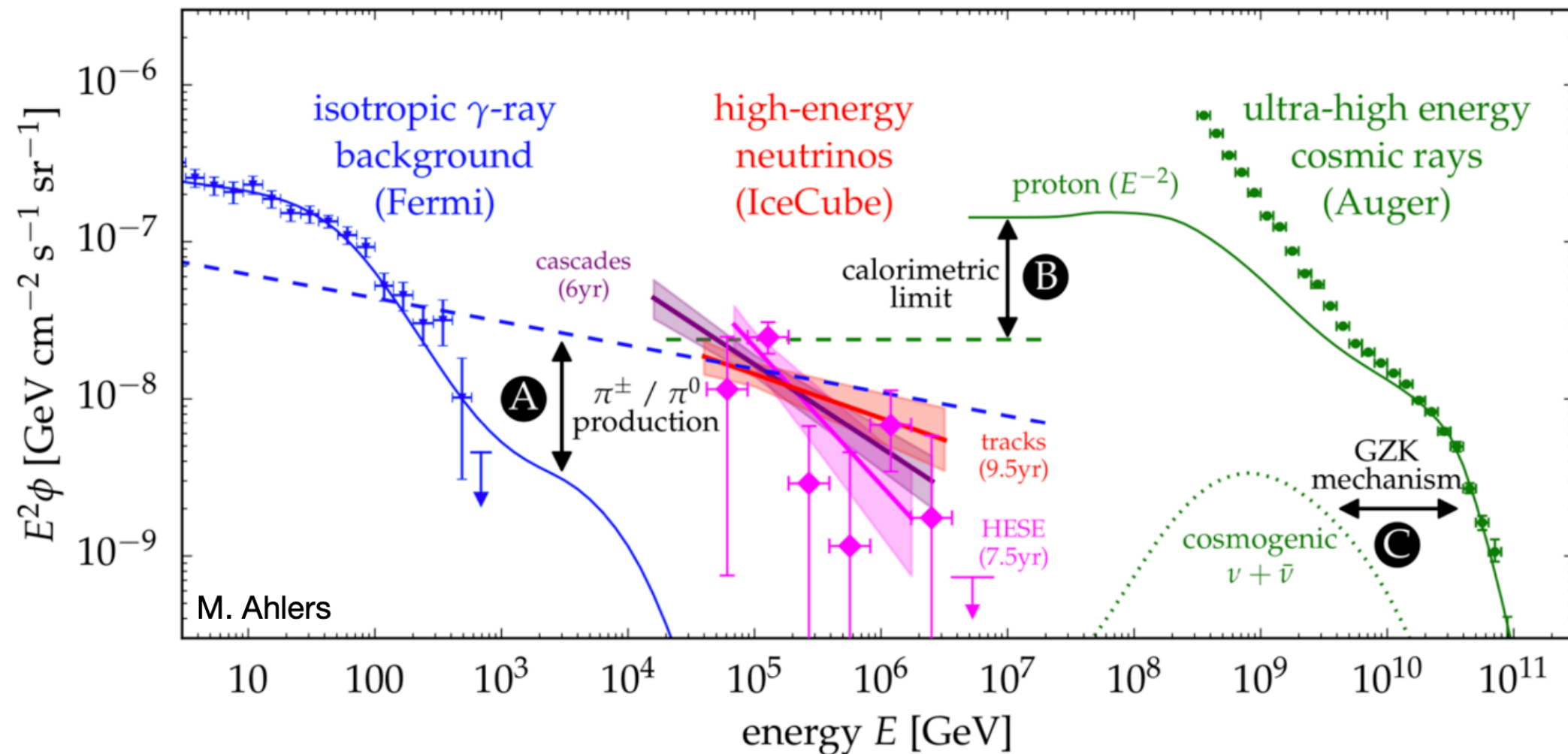


PoS ICRC(2019) 1031

- ◆ Robust measurements of the **cosmic neutrino flux** at $> 6\sigma$ confidence; slight tension between Northern sky and all-sky spectrum
- ◆ First potential source (**TXS 0506+056**) identified in 2017 through a strong multi-messenger campaign
- ◆ Have seen likely candidates for **astrophysical τ** and **Glashow resonance**; all SM cosmic messengers observed?
- ◆ No strong correlation with any source class in data, but interesting individual candidates (**NGC 1068**) and tighter constraints on populations emerging from new analyses
- ◆ Upcoming low-energy improvements (**IceCube-Upgrade**) and proposed expansion (**IceCube-Gen2**) will enable neutrino astronomy with an unprecedented sensitivity in the decades ahead

Thank You!

Backup



Similar energy density in **GeV gamma-rays** [Fermi-LAT], **TeV-PeV neutrinos** [IceCube] and **ultra-high energy cosmic rays (UHECR)** [Pierre-Auger] indicating a correlation at source

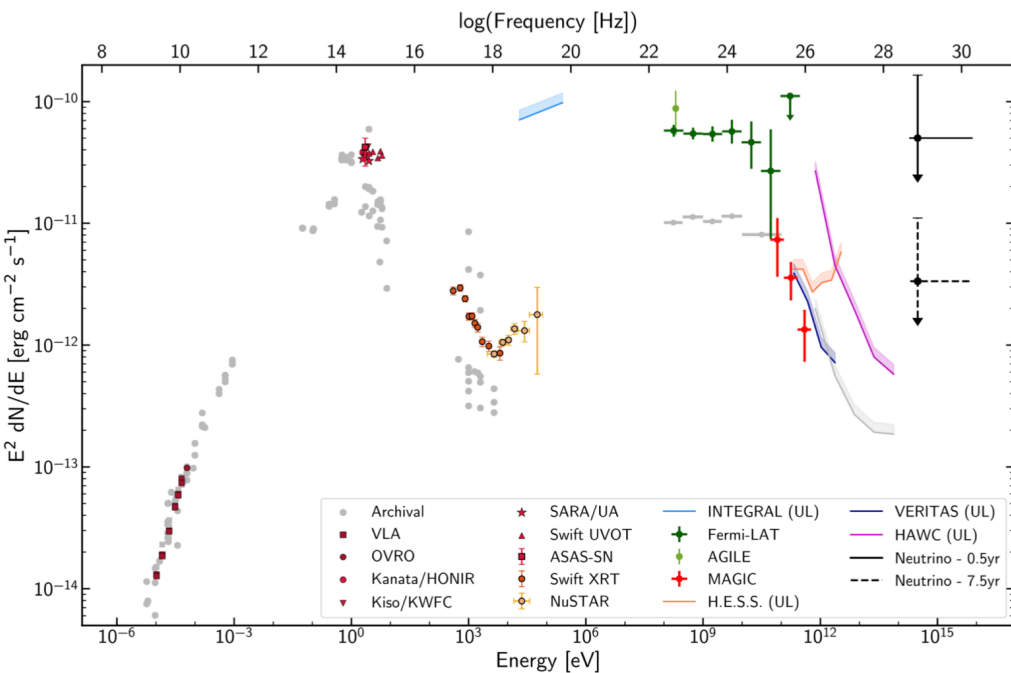
AMON - Astrophysical Multi-messenger Observatory Network

- ▶ IceCube releases public alerts in real time (~ 1 min) for ν -events of probable astrophysical origin through the Gamma-ray Coordinates Network (GCN)
- ▶ Followed-up by observatories like Fermi, MAGIC, SWIFT, ZTF etc. for coincident activity
- ▶ Since 2016; ~ 10 **Gold** ($> 50\%$ signalness) and ~ 30 **Bronze** ($> 30\%$ signalness) alerts/year
- ▶ First positive follow-up: **TXS 0506+056** ; observed in a gamma-ray flaring state

AMON ICECUBE_GOLD and _BRONZE EVENTS

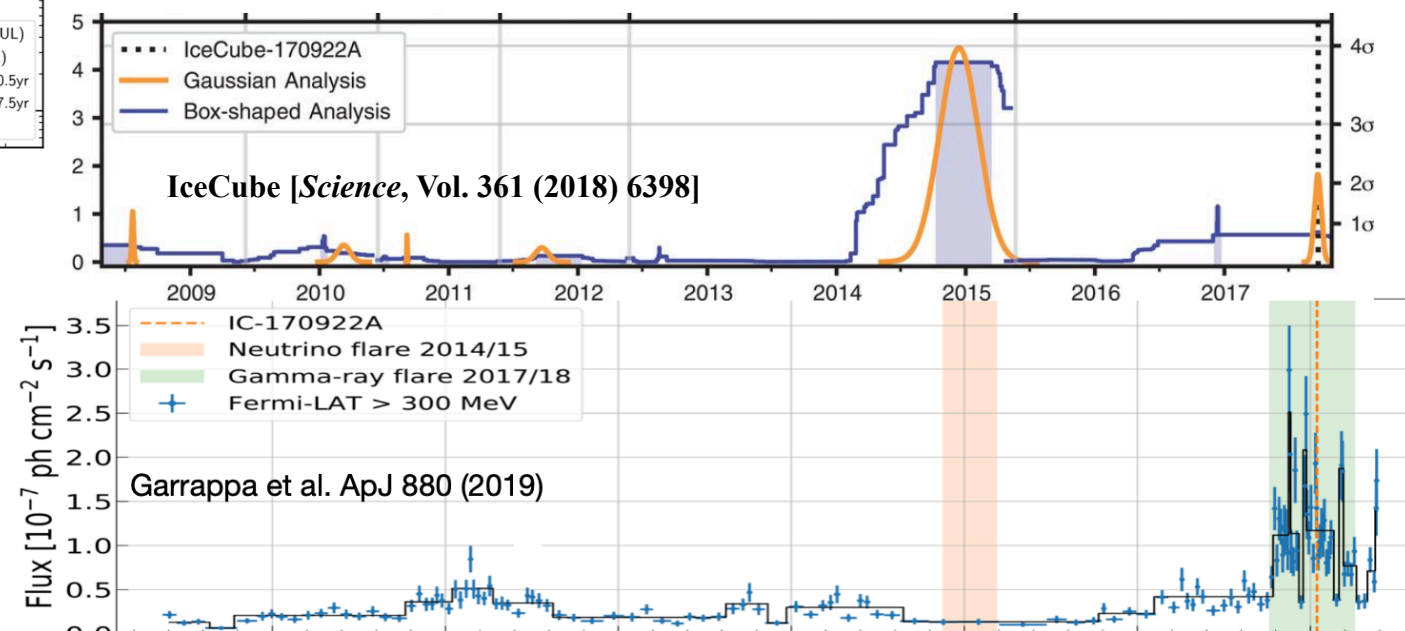
EVENT				OBSERVATION								
RunNum_EventNum	Rev	Date	Time UT	NoticeType	RA [deg]	Dec [deg]	Error90 [arcmin]	Error50 [arcmin]	Energy	Signalness	FAR [#yr]	Comments
134751_31476488	1	20/11/30	20:21:46.47	GOLD	30.5399	-12.0999	70.79	41.39	2.0347e+02	1.4696e-01	1.3222	IceCube Gold event. The position error is statistical only, there is no systematic added.
134751_31476488	0	20/11/30	20:21:46.47	GOLD	30.4950	-11.6137	42.65	16.61	2.0347e+02	1.4696e-01	1.3222	IceCube Gold event. The position error is statistical only, there is no systematic added.
134715_65785778	1	20/11/20	09:44:40.55	BRONZE	307.5299	+40.7700	280.79	158.40	1.5396e+02	5.0338e-01	0.2947	IceCube Bronze event. The position error is statistical only, there is no systematic added.
134715_65785778	0	20/11/20	09:44:40.55	BRONZE	307.8471	+40.1903	30.80	12.00	1.5396e+02	5.0338e-01	0.2947	IceCube Bronze event. The position error is statistical only, there is no systematic added.

The AMON network enables multi-messenger discoveries ($\nu + \gamma$ and also GW + γ) by bringing together Gamma-ray, Neutrino and GW observatories and vastly improving the significance of observations by any single experiment/instrument



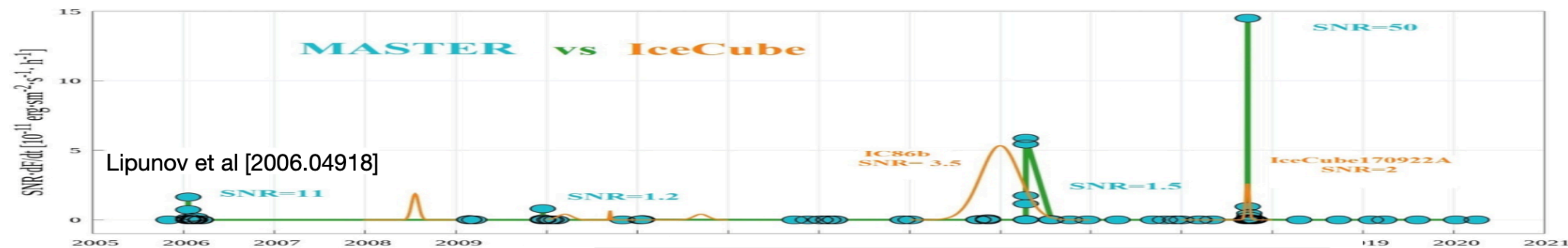
IceCube++ [Science, Vol. 361 (2018) 6398]

SED of TXS 0506+056 around the time of IC170922A, with neutrino flux expectation for 1 event in 6 months and 7 years



IceCube [Science, Vol. 361 (2018) 6398]

Garrappa et al. ApJ 880 (2019)



Lipunov et al [2006.04918]

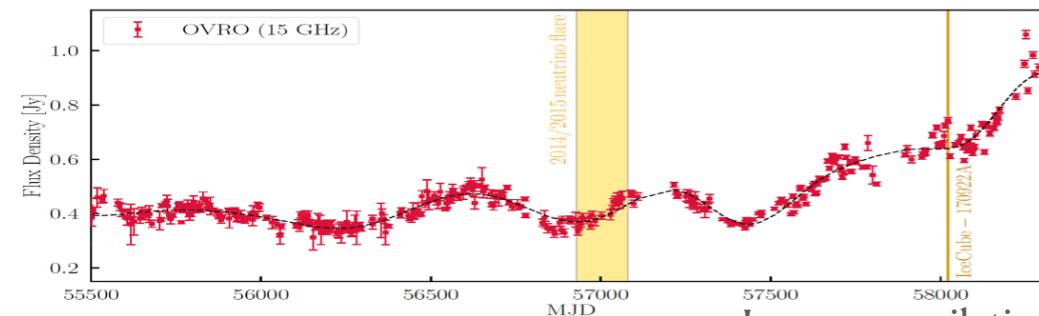
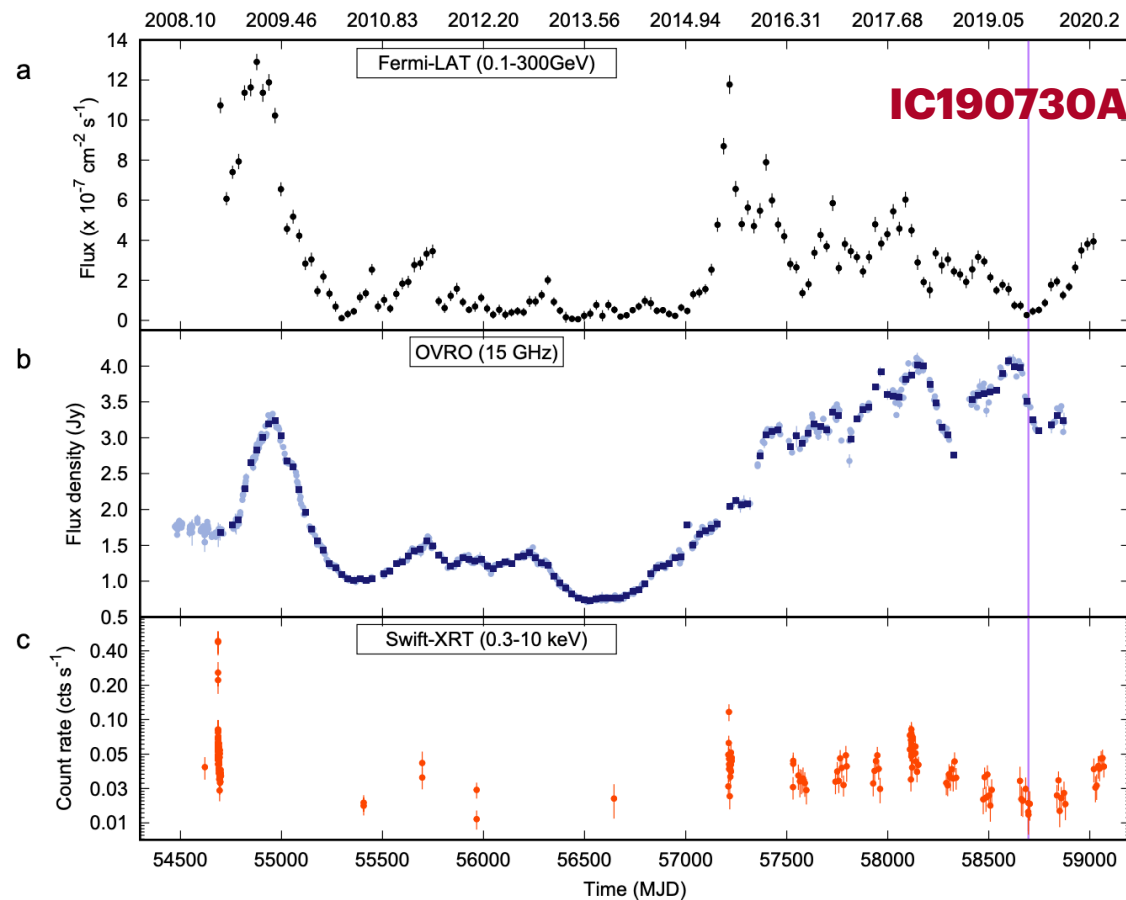


Image compilation Credit: Qinrui Liu

Neutrino alert and archival flare duration as observed by different instruments



IC190730A

Kun et al. ApJL 911 (2021) 2

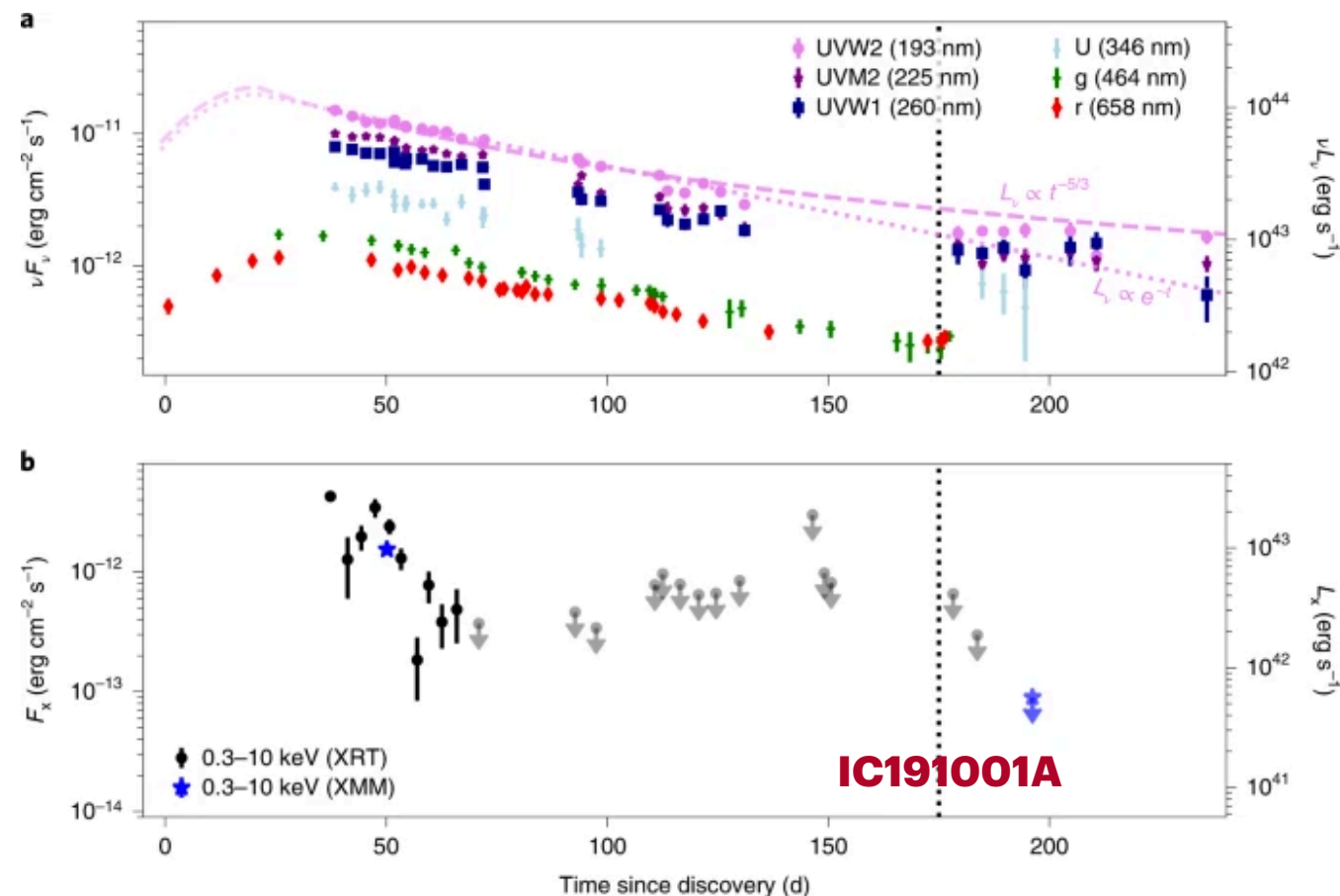
Coincident with blazar **PKS 1502+106**

Gamma-ray suppressed but flaring in radio at the time of neutrino alert

Coincident with radio emitting TDE **AT2019dsg** identified by ZTF

Taking into account bolometric flux, chance coincidence probability $\sim 0.2\%$

IC191001A



IC191001A

Resolving source populations with IceCube and IceCube-Gen2

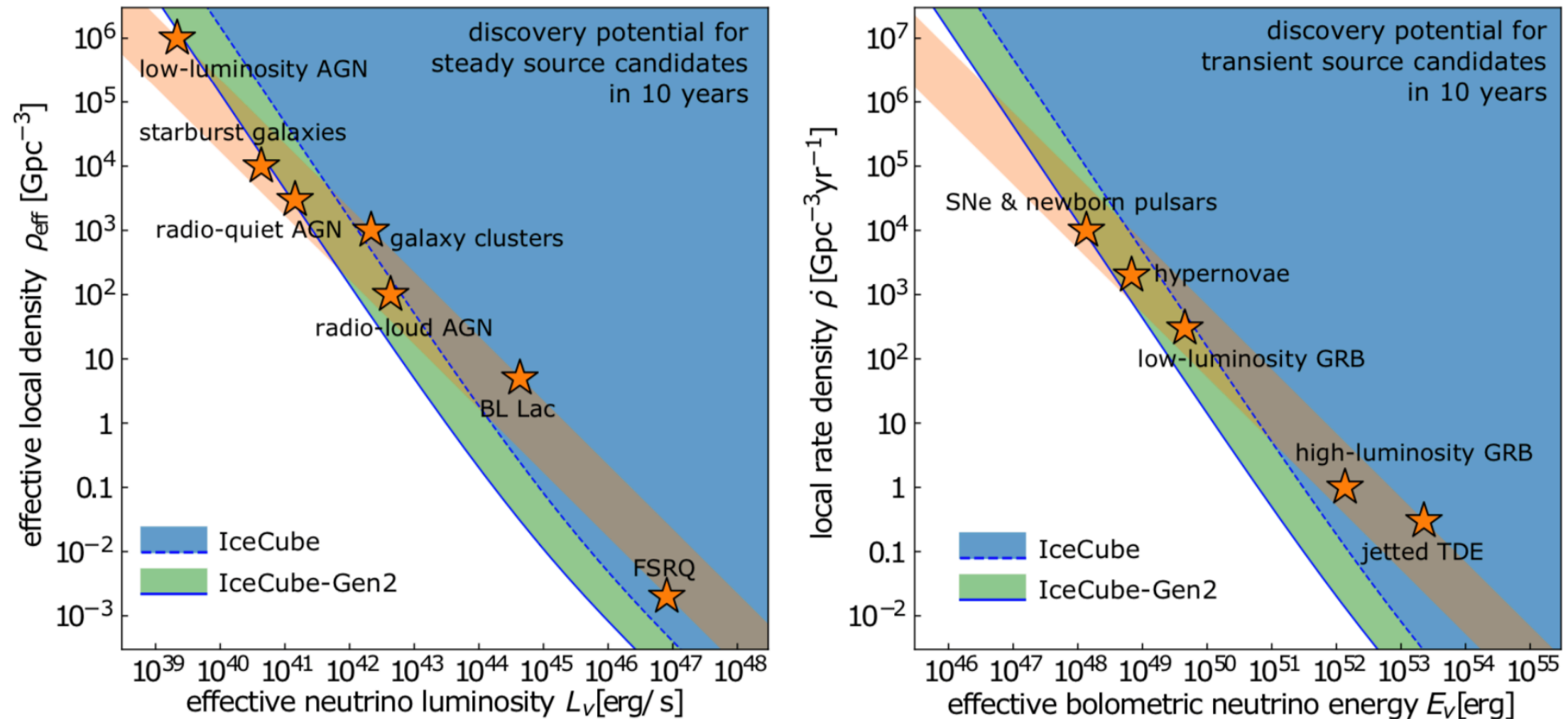
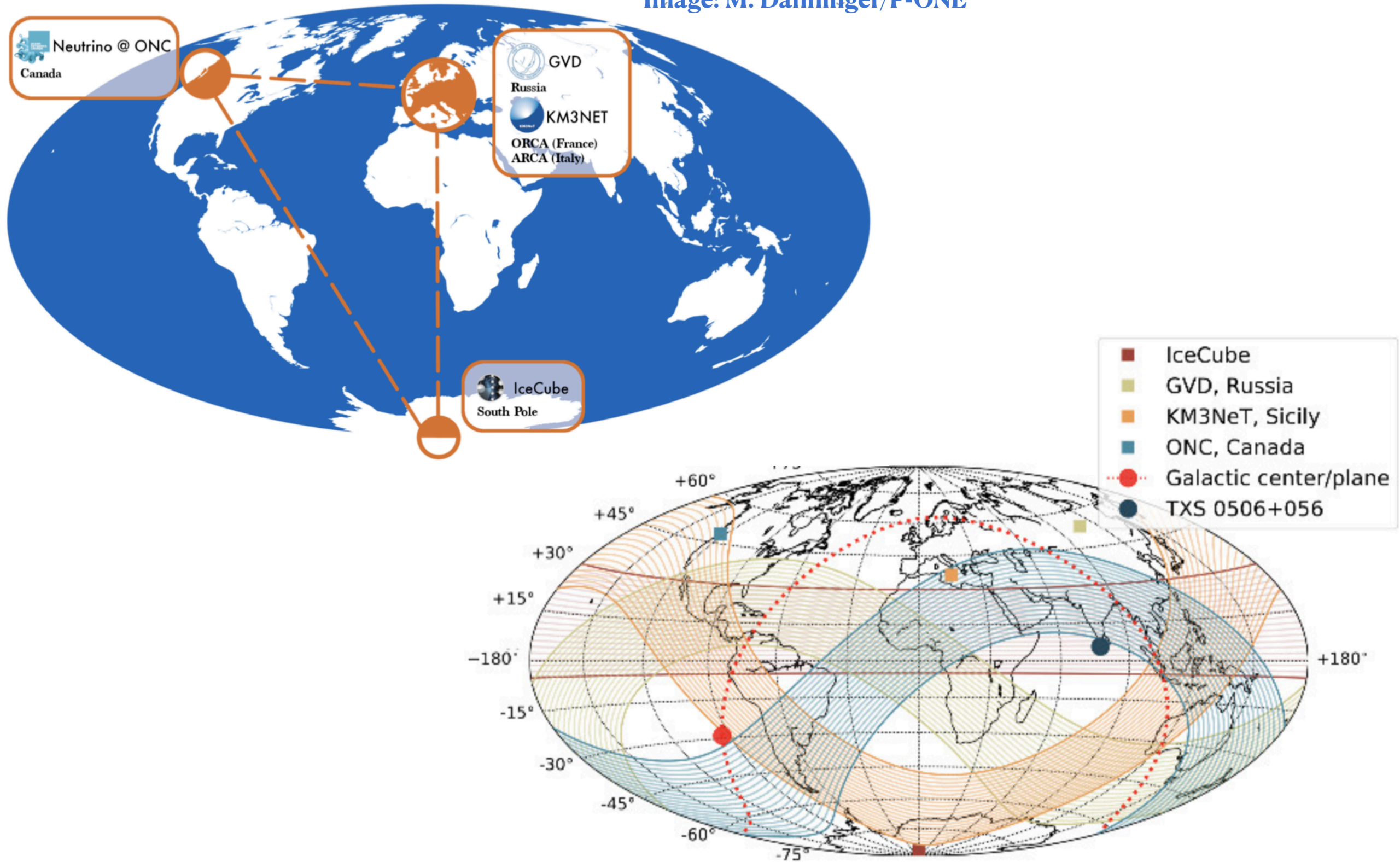
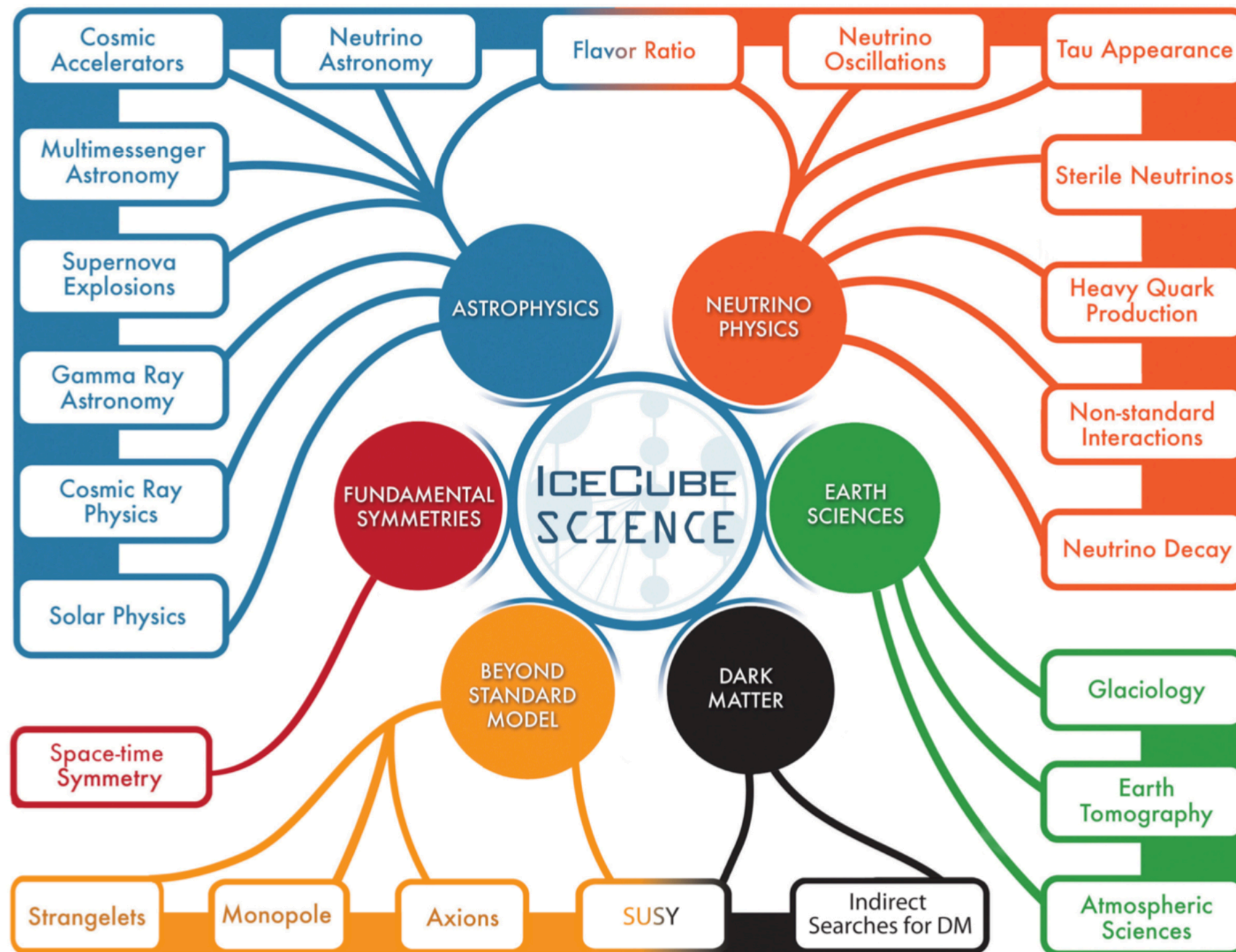


Image: M. Danninger/P-ONE







THE ICECUBE COLLABORATION

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Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

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DENMARK
University of Copenhagen

GERMANY
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